DISSERTATION

IMPROVING IRRIGATON SYSTEM PERFORMANCE THROUGH SCHEDULED WATER DELIVERY IN THE MIDDLE RIO GRANDE CONSERVANCY DISTRICT

Submitted by

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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY KRISTOPH-DIETRICH KINZLI ENTITLED IMPROVING IRRIGATION SYSTEM PERFORMANCE THROUGH SCHEDULED WATER DELIVERY IN THE MIDDLE RIO GRANDE CONSERVANCY DISTRICT BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

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ABSTRACT OF DISSERTATION

IMPROVING IRRIGATON SYSTEM PERFORMANCE THROUGH SCHEDULED WATER DELIVERY IN THE MIDDLE RIO GRANDE CONSERVANCY DISTRICT

This dissertation examines improving irrigation system performance in the Middle Rio Grande Valley in central New Mexico. Historically, the Middle Rio Grande Conservancy District practiced continuous on demand water delivery, which resulted in large diversions from the Rio Grande. Due to pressure related to the endangered Rio Grande silvery minnow (*Hybognathus amarus*), the Middle Rio Grande Conservancy District has been forced to manage water more effectively. To reach this goal while still providing farmers with adequate supplies, the Middle Rio Grande Conservancy District has employed scheduled water delivery. Scheduled water delivery introduces significant management challenges that can be addressed using Decision Support Systems (DSS). This dissertation presents the development, validation and implementation of a DSS in the Middle Rio Grande Conservancy District to facilitate scheduled water delivery. The development of the DSS represents a four year effort during which data were collected throughout central New Mexico to develop a real time model capable of predicting crop water demand and distributing irrigation water. This research verified the hypothesis that real time modeling using a Decision Support System is capable of predicting crop water demand and developing water delivery schedules to meet those demands. The field study conducted during the validation effort defined input parameters for the DSS and also had the contribution of quantifying farmer practices in the Middle Rio Grande Valley, which prior to this research were poorly understood. The implementation of the developed DSS was successful during the 2009 irrigation season and improved water delivery operations, while reducing the required water supply by 27%. Overall, the DSS provides the Middle Rio Grande Conservancy District with a powerful tool that can be used to schedule water delivery, determine legitimate water use, improve reservoir operations and sustain irrigated agriculture in the face of future water management challenges.

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For Edward Susak, my Grandfather

Although you never became the engineer you should have been and I never got to spend time with you, I am positive that your natural ability for problem solving and inquisitive nature have been passed on to me and allowed me to become an engineer.

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Last but most certainly not least, I would like to thank my family and friends. Without your support I could not have undertaken this decade long odyssey in college.

An Oma, Opa, Grandma, Mama, Papa, Stefan, und Leni. Vielen Dank fuer alles. Nach zehn langen Jahren sage ich CSU endlich Tchüss. Auf die Zukunft!

For all of you fishermen out there, never forget that:

"Eventually, all things merge into one, and a river runs through it. The river was cut by the world's great flood and runs over rocks from the basement of time. On some of the rocks are timeless raindrops. Under the rocks are the words, and some of the words are theirs………"

Norman Maclean, 1976

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CHAPTER 1 INTRODUCTION

Before year 2000, the Middle Rio Grande Conservancy District (MRGCD) in central New Mexico practiced continuous flow on-demand water delivery. Due to the concerns related to the endangered Rio Grande silvery minnow (RGSM) Hybognathus amarus, and increasing demands for water in other sectors, the MRGCD has opted to modernize its physical infrastructure and improve water delivery practices to more efficiently utilize diversions from the Rio Grande. This dissertation presents a comprehensive research effort since 2005 to improve water delivery practices utilizing scheduled water delivery, assisted by the introduction of a Decision Support System (DSS) in the Middle Rio Grande Valley. More specifically, it describes the development, validation, and implementation of a DSS in the Middle Rio Grande Conservancy District (MRGCD) and concurrent infrastructure modernization and SCADA (Supervisory Control and Data Acquisition) to make scheduled water delivery a reality.

1.1 PROBLEM STATEMENT

The Rio Grande is one of few large rivers in the American Southwest and it supports a diverse set of ecosystems as well as urban, industrial, interstate, and agricultural demands. Available water is fully allocated among users, and demand for the limited water supply continues to grow (Gensler et al. 2009; Oad et al. 2009; Oad and

Kinzli, 2006; Oad and Kullman, 2006) as the population increases and drought conditions persist in the Southwest. The native flow of the Rio Grande is limited, and cannot meet urban, industrial, interstate, ecological and agricultural demands during severe drought conditions. Competition for this limited water resource has greatly increased during the last decade and many complex issues have arisen as environmental concerns require a larger portion of available water (Kinzli and Myrick, 2009; Oad et al. 2009; Oad and Kinzli, 2006).

Concerns have been voiced that the Middle Rio Grande (MRG) Valley cannot support increasing water demand and that large irrigation diversions from the river limit the amount of water available in the valley. The State of New Mexico is concerned that large irrigation diversions are unsustainable and will not support future demands. A more recent concern, brought forth by the Endangered Species Act Collaborative Program (ESACP), is that large diversions from the river have negatively impacted the river ecosystem and wildlife, specifically the endangered RGSM.

1.2 NEED FOR RESEARCH

The MRGCD is the largest water user in the MRG Valley, utilizing significant river diversions that approach 40% of the available water (Oad et al. 2009; Oad and Kullman, 2006). Historic MRGCD diversion records were significantly higher than crop consumptive use. Although a significant portion of the water diverted is returned downstream through return flows, diversions are of primary concern because critical habitat for the RGSM may be diminished when water is diverted into irrigation canals. Considering limited water supplies and environmental concerns, the MRGCD has taken steps to decrease direct diversions from the Rio Grande (Gensler et al. 2009; Oad et al. 2009; Oad and Kullman, 2006).

Irrigated agriculture in the Middle Rio Grande Valley represents one of the oldest irrigated areas in the United States (Gensler et al. 2009). Irrigation in the region is tied to a long standing historical tradition dating back to irrigation practices introduced by Spanish settlers in the 1600's (Gensler et al. 2009). Prior to the arrival of the Spanish settlers, the area was being flood irrigated by the native Clovis, Anasazi, Mogollon and Hohokam peoples (Kinzli, 2008; Mac et al. 1998). The people of the MRG valley are firmly tied to the land and are fiercely protective of the agricultural tradition that has been established there for over 500 years. The goal of the MRGCD during drought and limited water supply is to sustain agriculture in the valley and preserve the lifestyle and heritage associated with irrigation. The problem facing the MRGCD over the last 10 years has been how to sustain irrigated agriculture in the MRG Valley with reduced river diversions. Scheduled Water Delivery (SWD), utilizing the knowledge of crop demand and available water supply, offers the ability to more effectively deliver and distribute water among all irrigators. Scheduled water delivery based on crop water requirements presents significant challenges in management, data collection, and data processing.
In order to utilize water delivery schedules and analyze data related to crop demand it was clear that the MRGCD needed a tool to facilitate the development of water delivery schedules.

1.3 DESCRIPTION OF SCHEDULED WATER DELIVERY (SWD)

Scheduled Water Delivery (SWD) is used in irrigation systems worldwide to improve water delivery and to support water conservation. In SWD, lateral canals receive water from the main canal according to their need for water, allowing water use in some laterals while others are closed. In addition to this water scheduling among laterals, there can be scheduling within laterals whereby water use is distributed in turn among farm turnouts or check structures along a lateral. By distributing water among users in a systematic fashion based on crop demand, an irrigation district can decrease water diversions and still meet crop water use requirements. A well-managed program of scheduled water delivery is able to fulfill seasonal crop water requirements in a timely manner, but requires less water than continuous water delivery. Figure 1.1 displays scheduled water delivery.

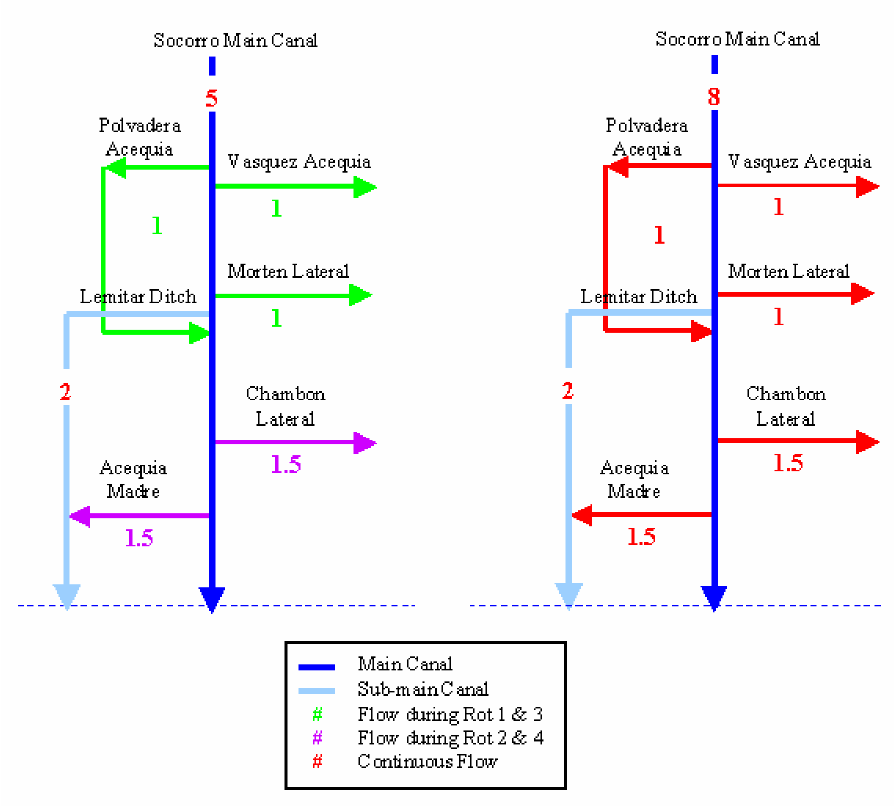


Figure 1.1: Schematic Showing Scheduled Water Delivery (Barta, 2003)

Previous research by Barta (nee Kullman) (Oad and Kullman, 2006; Barta, 2003) examined operational procedures that would reduce river diversions in the Middle Rio Grande Valley. Kullman found that scheduled water delivery in the MRGCD could theoretically reduce river diversions by up to 40% (Oad and Kullman, 2006).

1.4 HYPOTHESIS

The overall research premise for this dissertation was that real time modeling using a DSS is capable of predicting crop water demand and creating water delivery schedules to meet those demands. An additional premise of this dissertation was that a

DSS could be implemented in the MRGCD to effectively and equitably manage water delivery operations.

1.5 OBJECTIVES AND SCOPE

The overall objective of the research presented in this dissertation was to develop, validate, and implement a DSS in the MRGCD. The objective of the DSS validation was to verify that the DSS was capable of predicting crop water demand on a real time basis and that appropriate water delivery schedules could be developed to meet crop requirements. An additional objective of this research was to implement the DSS to facilitate scheduled water delivery in the MRGCD.

This research did not focus on several factors that affect the MRGCD. Complex issues related to the ESA in the MRG Valley were not addressed in this research. It is the opinion of the USFWS that irrigated agriculture diverts excessive water from the river that ultimately impacts the survival of the RGSM (USFWS, 2003a). This research acknowledged that a healthy river ecosystem is paramount to subsequent demands and aimed to limit river diversions to meet the goal of protecting the RGSM and the river ecosystem. The MRGCD provides irrigation services to six Native American pueblos. Pueblo irrigators are recognized as having senior water rights and operate separately from MRGCD management. This research did not address river diversions for pueblo irrigators nor will it attempt to schedule water delivery in the six Native American pueblos.

1.6 APPROACH

In order to realize scheduled water delivery in the MRGCD it was necessary to take a multi-faceted approach. The first step in realizing scheduled water delivery was developing a Decision Support System (DSS) that was capable of calculating irrigation schedules and water delivery plans based on crop water demand. After the development of the DSS was accomplished it was necessary to validate the programming logic to verify the hypothesis that a DSS is capable of predicting crop water demand and creating water delivery schedules to meet that demand. It was also necessary to determine specific input parameters for the MRGCD.

The related step in realizing scheduled water delivery consisted of linking the DSS to the MRGCD SCADA (Supervisory Control and Data Acquisition) program. The MRGCD is currently modernizing its physical infrastructure including the use of SCADA. The modernization and SCADA incorporation is not a part of the research presented in this dissertation and was carried out by the MRGCD starting in 1995. This program is addressed in this dissertation because flow rates through the canal network were not known prior to the infrastructure modernization effort and it would have been impossible to achieve scheduled water delivery without proper flow measurement. Additionally, the DSS was linked to the MRGCD SCADA network to provide real time water delivery recommendations and management.

The third step in realizing SWD involved the implementation of the developed DSS in everyday water operations to evaluate the hypothesis that a DSS could be utilized to manage complex water delivery operations. Implementation began by linking DSS flow recommendations to the MRGCD SCADA network. Implementation also entailed training MRGCD personnel, providing on site technical support of the DSS, and gaining public acceptance of SWD through a public outreach program. Figure 1.2 displays the components that were necessary to achieve scheduled water delivery in the MRGCD.

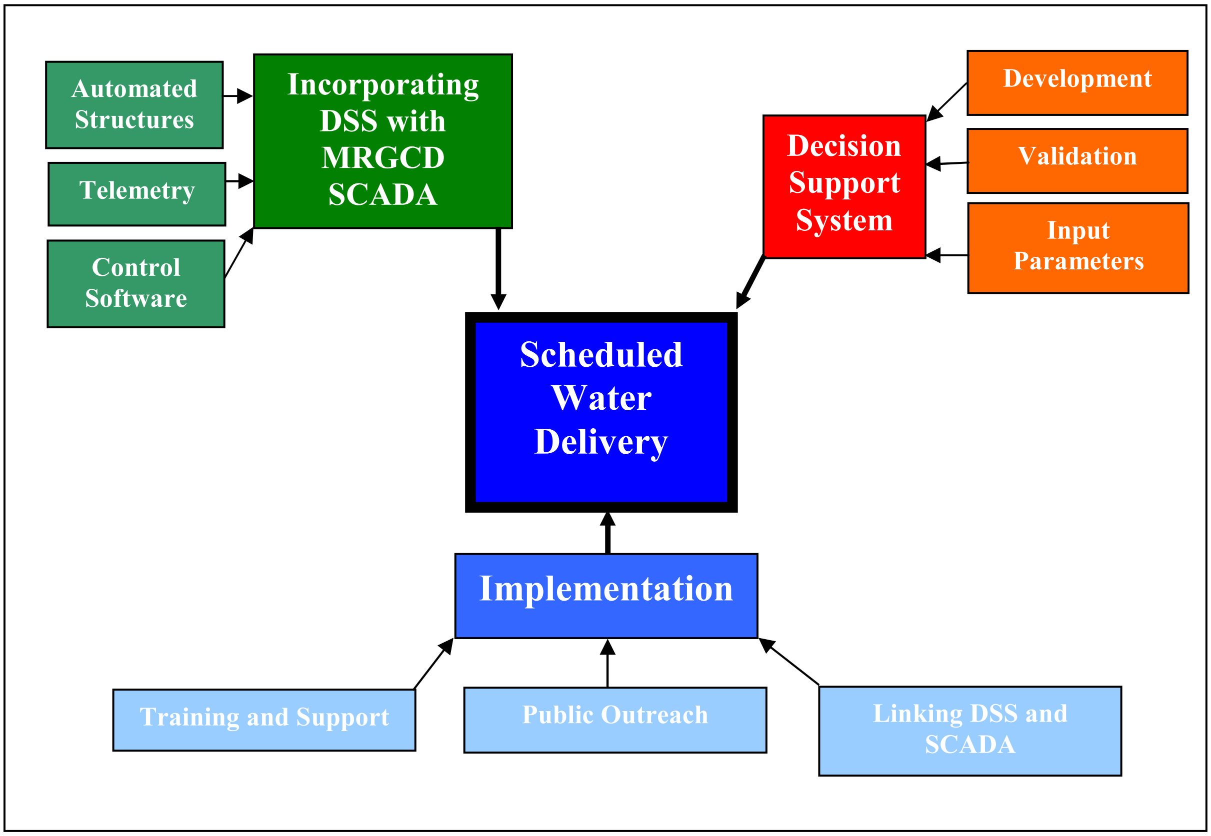


Figure 1.2: Approach to Achieving Scheduled Water Delivery

1.7 DISSERTATION ORGANIZATION

Chapter 2 provides background information on the Middle Rio Grande Valley and the Middle Rio Grande Conservancy District. This chapter explains the water supply and water demands in the valley, including the Rio Grande silvery minnow, the Rio Grande Compact, and describes the Middle Rio Grande Conservancy District in detail. This chapter also presents previous research conducted by Colorado State University in the Middle Rio Grande Valley.

Chapter 3 presents a literature review of decision support systems (DSS). This chapter defines what a decision support system is and examines river management with DSS models. This chapter also presents the principles of irrigated agriculture related to a DSS, which include evapotranspiration, crop consumptive use, crop coefficients, readily available moisture, and crop irrigation requirement. Two DSS models that have been developed for irrigation systems are also examined in this chapter.

Chapter 4 describes the development of the MRGCD DSS. This chapter provides a detailed description of the DSS and presents the overall model framework and structure. The three modules that comprise the DSS (Water Demand Module, Supply Network Module, Irrigation Scheduling Module) are described and the model programming is also explained. The development of the DSS schematics for the four MRGCD Divisions is also described.

Chapter 5 addresses the validation of the MRGCD DSS and research that was conducted to determine the DSS input parameters. The instrumentation of eight farm fields is described and results related to on farm application efficiency, RAM remaining, soil moisture depletion and yield are presented. A canal seepage study that was conducted to determine losses from the delivery system in the MRGCD is described, as well as the validation of the model programming logic and model performance.

Chapter 6 describes the implementation of scheduled water delivery utilizing the developed DSS during the 2009 irrigation season. This chapter describes how the DSS was linked to the MRGCD SCADA network and explains the training that was conducted to facilitate scheduled water delivery. This chapter also addresses a public outreach campaign that was conducted to gain support and understanding for scheduled water delivery. The results of scheduled water delivery in the MRGCD during the 2009 irrigation season are presented along with benefits that the MRGCD has realized through its implementation. These benefits include determining an appropriate water use, making irrigated agriculture a more efficient water user, reducing river diversions, providing for minimum flow requirements, and contributing towards a healthy ecosystem in the Middle Rio Grande. The benefits that scheduled water delivery have had for MRGCD reservoir operations and how the DSS will be used in the future is also addressed. This chapter also presents benefits that scheduled water delivery utilizing a DSS could have in other arid regions and throughout the world.

Chapter 7 presents conclusions and summarizes the dissertation and the research necessary to realize scheduled water delivery in the MRGCD. The contribution this research has for the field of agricultural engineering is also presented. This chapter also presents future studies that would continue, augment, and expand the research presented in this dissertation.

The units of measurement used throughout this dissertation are English units to ease local understanding of the material and to facilitate the transfer of data to the Middle Rio Grande Valley and elsewhere in the United States. The journal articles presented in the Appendix have been converted to metric units because of standard scientific publication requirements.

CHAPTER 2 BACKGROUND AND PREVIOUS RESEARCH

This chapter provides background information on water supply and its use in the Middle Rio Grande (MRG) Valley. The purpose is to develop a general understanding of water supply and demand, and how water is allocated among various users in the MRG Valley. The water sources and competing water users are examined to provide the framework in which the Middle Rio Grande Conservancy District operates. Previous research by Colorado State University in the MRG Valley is also reviewed in this chapter.

2.1 DESCRIPTION OF MIDDLE RIO GRANDE VALLEY

The Middle Rio Grande Valley runs north to south through central New Mexico from Cochiti Reservoir to the headwaters of Elephant Butte Reservoir, a distance of approximately 175 miles. Figure 2.1 displays an overview of the MRG Valley. The valley is narrow, with the majority of water use occurring within five miles on either side of the river. The bosque (Spanish for forest) of native cottonwood, Populus fremontii and non-native salt cedar, Tamarix ramosissima is supported by waters of the Rio Grande. Surrounding the bosque is widespread irrigated farming. From an aerial viewpoint, the river valley appears as a meandering ribbon of green in contrast to the surrounding semi-arid desert (Barta, 2003). The City of Albuquerque and several smaller communities are located in and adjacent to the MRG Valley. Although the valley receives less than 10 inches of rainfall annually, it supports a rich and diverse ecosystem of fish and wildlife and is a common resource for communities in the region (DuMars and Nunn, 1993)

Figure 2.1: Overview of Middle Rio Grande Valley (Barta, 2003)

2.2 ORIGIN OF WATER SUPPLY

Water supply in the Middle Rio Grande Valley consists of native surface water, groundwater, and a trans-mountain diversion from the San Juan River. Surface water storage in the MRG Valley is limited to a small number of reservoirs that are operated by the U.S. Army Corps of Engineers, U.S. Bureau of Reclamation, and Middle Rio Grande Conservancy District.

2.2.1 Native Flow

The Rio Grande originates in southwest Colorado’s San Juan Mountain Range. The Rio Grande flows south through the center of New Mexico and eventually turns east to form the border between the state of Texas and Mexico. The major tributaries of the Rio Grande are the Conejos River in Colorado, the Chama, Jemez, Rio Puerco and Rio Salado Rivers in New Mexico and the Pecos River in Texas. The Rio Grande empties into the Gulf of Mexico at Boca Chica Beach, Texas (Google Earth, 2006). The Rio Grande Basin within the lower part of Colorado and within New Mexico south to Elephant Butte can be seen in Figure 2.1.

Water in the MRG Valley is fully appropriated and depletion of surface water is limited by the Rio Grande Compact of 1938. Set forth in the Compact is a schedule of deliveries of Native Rio Grande water to New Mexico from Colorado and from New Mexico to Texas. New Mexico’s required delivery to Texas is determined using gaged flow on the Rio Grande at Otowi Bridge near San Ildefonso Pueblo. Water deliveries to Texas occur at Elephant Butte Reservoir. Water obligation to Texas is measured on a sliding scale and is a percentage of the flow passing Otowi Bridge. For example, in an average year when 1,100,000 acre feet (af) of water passes Otowi Bridge, approximately 393,000 af of the 1,100,000 af is available for use in the MRG Valley (Rio Grande Compact Commission, 1997). According to the sliding scale, the maximum amount of native flow available for use in the MRG Valley is 405,000 af per year (Rio Grande Compact Commission, 1997).

2.2.2 Groundwater

Groundwater supply in the MRG Valley is considered to be in a stream-connected aquifer (Gallea, 2005). In the vicinity of Albuquerque, the once connected aquifer has become disconnected from the Rio Grande due to extensive pumping estimated at 155,500 af/yr (SSPA, 2000). In stream-connected aquifers, pumping impacts on the river are realized immediately, while in disconnected aquifers observed pumping impacts on native surface flow are subject to a time delay. Because groundwater has been pumped so excessively in the Albuquerque area and groundwater pumping results in depletions of already fully appropriated native flows, groundwater does not represent an additional source of supply in the MRG Valley (SSPA, 2000).

2.2.3 San Juan Chama Trans Mountain Diversion

The San Juan Chama Project (SJC) consists of a system of diversion structures and tunnels that allow trans-mountain movement of water from the San Juan River Basin to the Rio Grande Basin. The project takes water from three upper tributaries of the San Juan River, namely the Navajo, Little Navajo, and Blanco Rivers (USBR, 2005), and delivers water through a system of siphons and tunnels that converge at a point on the

Navajo River. From there the water is transported to the Rio Grande Basin via the 12.8 mile long, 950 cfs capacity Azotea Tunnel (USBR, 2005). The water enters the Rio Grande Basin through Azotea and Willow Creeks and flows downstream to be stored in Heron Reservoir. The project was designed by the U.S. Bureau of Reclamation (USBR) and was completed in 1971. The SJC Project provided an average of 75,844 af/yr from 1990 to 1998 to the MRG Valley (SSPA, 2000). The primary purpose of the diversion is to supplement the supply for the municipal, agricultural and industrial water users in the MRG Valley (USBR, 2005). From the average annual diversion of the SJC Project, the Middle Rio Grande Conservancy District (MRGCD) can withdraw 20,900 af for agricultural use (USBR, 2005).

2.3 WATER DEMAND

Water demand in the MRG Valley is comprised of multiple users which include the (1) Endangered Species Act, (2) urban and industrial users, (3) the Rio Grande Compact, and (4) the Middle Rio Grande Conservancy District. With water being fully allocated, the four main users compete for limited water resources as the population in the MRG Valley expands. Consumptive uses from vegetation along 175 miles of the MRG and water evaporation from the river's surface add an additional demand to an already fully allocated water resource. Complete allocation and consumptive use along the river have led to water disputes, which are exacerbated during drought conditions.

2.3.1 The Endangered Species Act: Rio Grande Silvery Minnow

The Rio Grande silvery minnow (RGSM) is one of seven species in the genus Hybognathus found in the United States (Bestgen and Propst, 1996). The RGSM is small for the genus Hybognathus and they rarely exceed a total length of 3.5 inches (Bestgen and Platania, 1991). The RGSM is so named because the sides and back appear silver to olive in color (Bestgen and Propst, 1996). Some specimens may exhibit a broad greenish mid dorsal strip and the lower sides and abdomen are generally silver (Bestgen and Propst, 1996). Figure 2.2 displays two adult Rio Grande silvery minnow.

Figure 2.2: Rio Grande Silvery Minnow (*Hybognathus* *Amarus*)

Historically the RGSM thrived in 2,465 miles of rivers in New Mexico and Texas (Kinzli and Myrick, 2009). Today the RGSM has been extirpated from 95% of its historical range to the Middle Rio Grande between Cochiti Dam and Elephant Butte

Reservoir (USFWS, 2003a; USFWS, 2002; Bestgen and Platania, 1991; Edwards and Contreras-Balderas, 1991; Propst et al. 1987). Figure 2.3 displays the past and present distribution of the RGSM. Due to the extreme decline of the RGSM it was classified as a Federal Endangered Species in 1994 (Federal Register, 2002; USFWS, 2002).

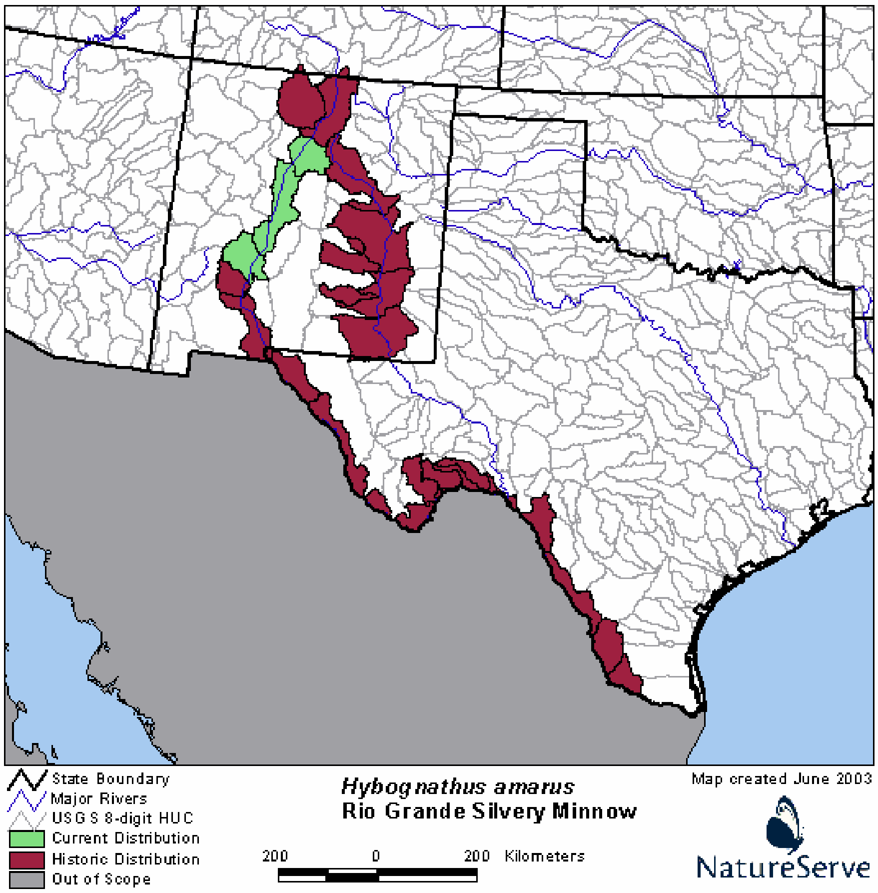


Figure 2.3: Historic and Current Distribution of the Rio Grande Silvery Minnow (*Hybognathus Amarus)* (USFWS, 2006)

The RGSM spawns pelagically; the onset of spawning coincides with increased stream flow from spring runoff (Bestgen and Propst, 1996). Spawning induces broadcast fertilization with each female laying between 1,000 and 10,000 eggs over a period of eight hours (Bestgen and Propst, 1996). The eggs are semi-buoyant and drift downstream in the water column until they hatch 24 to 48 hours later (Platania and Altenbach, 1998; Bestgen and Propst, 1996).

Habitat utilized by adult RGSM are mostly low velocity areas such as eddies, pools, debris piles, backwaters and side channels (Dudley and Platania, 2007; USFWS, 2003a). Minnows favor these areas due to low velocity and higher rates of primary productivity (Kinzli and Myrick, 2009). According to the USFWS, channelization of the Rio Grande, water management and subsequent use in the MRG Valley have contributed to a large reduction of suitable habitat for the RGSM (USFWS, 2003b). Other factors linked to the endangered classification of the Rio Grande silvery minnow include habitat modifications, altered flow regimes resulting from dam operations, periodic drying of the river, non-native fishes, hybridization and disruption of egg dispersal (Dudley and Platania, 2007; Platania and Altenbach, 1998; Bestgen and Propst, 1996; Cook et al., 1992; Platania, 1991; Bestgen and Platania, 1990; Bestgen et al., 1989)

The USBR and the U.S. Army Corp of Engineers (USACE) in consultation with the USFWS have developed water operations and river maintenance procedures in various biological assessments and opinions that are critical to the survival and recovery of the RGSM (USFWS, 2003a; USFWS 2003b). These procedures include timing of flow requirements to help initiate spawning, implementing minimum flow requirements along the Rio Grande, and realizing habitat improvements to help with the survival of the RGSM (USFWS, 2003b). The biological assessments led to the designation of critical habitat for the RGSM in March 2003. The critical habitat designation forces federal agencies, the State of New Mexico and the MRGCD to take actions that will ensure the survival of the RGSM (Gallea, 2005). The area designated as critical habitat includes the entire Rio Grande from Cochiti Dam to Elephant Butte Reservoir, and encompasses the MRGCD. A journal article by Kinzli and Myrick, (2009) that describes the RGSM and habitat restoration in detail is included as Appendix A.

To aid in the recovery of the RGSM the Albuquerque Bernalillo County Water Utility Authority has developed a rearing and breeding facility at the Albuquerque Biological Park, with the goal of rearing 50,000 young fish per year (VHGA, 2006). The US $1.7 million facility is designed to produce 50,000 minnows a year with 25,000 minnows to be returned to the river and 25,000 to be retained for future captive spawning (VHGA, 2006). The facility consists of a 50,000 gallon outdoor naturalized refugium as well as a 3,500 square foot building with tiers of aquarium tanks that contain tens of thousands of juvenile minnows. The donut-shaped outdoor refugium varies in depth from about one inch to two feet. Pumps control the current to mimic the natural flows of the Rio Grande (VHGA, 2006). The bottom surface is a mixture of sand, gravel and silt. To date 370,000 RGSM have been reared at the facility and released into the Rio Grande. Figure 2.4 displays the Albuquerque RGSM refugium.

Figure 2.4: Albuquerque Naturalized Refugium (VHGA, 2006)

An additional naturalized refugium was completed in the town of Los Lunas in 2008 and became operational during the summer of 2009. The $1.2 million Los Lunas refugium is a cutting edge rearing facility designed to mimic the flood cycles found in the historic Rio Grande (Tave et al. 2008). The facility consists of a 458 ft meandering stream with a re-circulating water system (Haggerty et al. 2008). The flow depth can be adjusted from 0.6 to 2.9 ft with a total water area of 0.27 acres and volume of 161,000 gallons (Tave et al. 2008). The refugium contains habitat features preferred by the RGSM such as shallow sandy shelves, eddies, backwaters, and off-channel pools (Haggerty et al. 2008). The refugium also contains natural substrate and native bank vegetation, which will be flooded to induce RGSM spawning (Tave et al. 2008). The overall goal of the refugium is to produce RGSM for augmentation in a natural setting to reduce domestication (Tave et al. 2008). Figure 2.5 displays Los Lunas RGSM refugium.

Figure 2.5: Los Lunas Naturalized RGSM Refugium

2.3.2 Urban and Industrial

In 2000, there were approximately 690,000 inhabitants in the MRG Valley (USGS, 2002). Of those 690,000 inhabitants, 445,000 (65%) people lived in the greater Albuquerque area (USCB, 2000). Population in the MRG Valley has increased steadily since the 1950's and large growth in the industrial sector has occurred with companies such as Intel, Honeywell, and General Electric Aircraft Engines centered in Albuquerque. Development in the area has been supported by the San Juan Chama Project and increased groundwater pumping in the vicinity of Albuquerque (Barta, 2003). In 2009 the Albuquerque water treatment plant completed an inflatable diversion dam and began to use SJC project water that was previously available for other entities. The utilization of this water exacerbated the already complex and intricate delivery of water throughout the valley. A shift from rural to urban and industrial use has increased groundwater demand in the region (Hansen and Gorbach, 1997). Unfortunately, since the only water source for Albuquerque is the SJC project and groundwater, the aquifer depletion rates continue to outstrip recharge rates (Earp et al; 1998). Although groundwater supports current urban and industrial demand, it is not a sustainable option for the future.

2.3.3 Rio Grande Compact

Native flow of the Rio Grande is allocated annually among states insuring an equitable apportionment for use (Barta, 2003) and water is allocated to Colorado, New Mexico and Texas according to the Rio Grande Compact. The Rio Grande Compact uses credits and debits to allocate water rights to the three states and limits the amount of debit or under-delivery of water to downstream states. A credit happens when there is an over-delivery of water to the downstream state, while a debit happens when there is an under-delivery of water to the downstream state. Colorado can acquire a debit of up to 100,000 acre feet to New Mexico and New Mexico can accrue a debit of up to 200,000 acre feet to Texas (Rio Grande Compact Commission, 1997).

The portion of the Rio Grande under New Mexico jurisdiction starts at the Colorado-New Mexico line and ends at Elephant Butte Reservoir. The difference between the amount of water passing through Otowi Bridge and the amount necessary to pass through the Elephant Butte Dam, plus water supply between these two points, is the amount of surface water available for depletion in the MRG Valley (SSPA, 2000). Under normal flow conditions the Rio Grande Compact allocates 400,000 acre feet for use in the MRG Valley.

Persistent drought conditions in the MRG Valley and demands associated with the RGSM have reduced stored water available for irrigation and for meeting New Mexico's compact obligations to Texas. Under low water conditions Article VII of the Rio Grande Compact prohibits water storage in reservoirs above Elephant Butte Reservoir that were constructed after 1929 (Barta, 2003). In practice, Article VII prohibits storage of Rio Grande water for use in the MRG Valley until the allocated delivery to Texas in Elephant Butte Reservoir reaches 400,000 acre feet.

2.3.4 Middle Rio Grande Conservancy District

The Middle Rio Grande Conservancy District (MRGCD) may be one of the oldest operating irrigation systems in North America (Gensler et al. 2009). Prior to Spanish settlement in the 1600s the area was being flood irrigated by the native Pueblo Indians. At the time of Albuquerque's founding in 1706 the ditches, that now constitute the MRGCD, were in already existence and were operating as independent acequia (tertiary canal) associations (Gensler et al. 2009). Acequias consisted of farmer groups that maintained individual irrigation canals. The acequia system was introduced to the MRG

Valley by Spanish settlers. In acequia communities, each farmer was responsible for maintaining a certain length of canal and would in return receive irrigation water. The use of irrigation water was managed by an elected mayordomo (ditch-rider or water master) (Gensler et al. 2009).

Irrigated agriculture in the MRG Valley reached its greatest extent in the 1880s, but thereafter underwent a significant decline caused by an overabundance of water. By the early 1920s inadequate drainage and periodic flooding resulted in water logging throughout the MRG Valley. Swamps, seeps, and salinization of agricultural lands were the result. In 1925, the State of New Mexico passed the Conservancy Act, which allowed for the creation of the MRGCD, which was accomplished by combining 79 independent acequia associations into a single entity (Gensler et al. 2009; Shah, 2001). Over the next twenty years the MRGCD provided benefits of irrigation, drainage, and flood control; however, by the late 1940's, the MRGCD was financially unstable and further rehabilitation of structures was required. In 1950, the MRGCD established a 50-year contract termed the Middle Rio Grande Project with the USBR to provide financial assistance, system rehabilitation, and system improvement. System improvements and oversight from the USBR continued until 1975 when the MRGCD resumed operation and maintenance of the system. The loan from the USBR to the MRGCD for improvements and operational expenses was repaid in 1999 (Shah, 2001). Currently the MRGCD operates and maintains nearly 1,500 miles of canals and drains throughout the valley in addition to nearly 200 miles of levees for flood protection.

Water use in the MRG Valley has not been adjudicated but the MRGCD holds various water rights and permits for irrigation (Oad and Kullman, 2006). Some users in the MRGCD hold vested water rights that are surface rights claimed by land owners who irrigated prior to 1907 (SSPA, 2002). Most water users in the MRGCD receive water through state permits held by the MRGCD. In 1930, the MRGCD filed two permits (#0620 and #1690) with the Office of the State Engineer that allow for storage of water in El Vado reservoir (180,000 acre feet capacity), release of the water to meet irrigation demand, and diversion rights from the Rio Grande to irrigate lands served by the MRGCD. The permits allow the MRGCD to irrigate 123,000 acres although only 70,000 acres are actually irrigated (MRGCD, 2007). This acreage includes roughly 10,000 acres irrigated by pueblo farmers. The MRGCD charges water users an annual service charge per acre to operate and maintain the irrigation system. In 2000 the MRGCD charged $28 per acre per year for the right to irrigate land within the district (Barta, 2003).

2.3.4.1 Physical System

The MRGCD services irrigators from Cochiti Reservoir to the Bosque del Apache National Wildlife Refuge. An overview map of the MRGCD is displayed in Figure 2.6. Irrigation structures managed by the MRGCD divert water from the Rio Grande to service agricultural lands, that include both small urban landscapes and large scale production of alfalfa, corn, vegetable crops such as chili and grass pasture. The majority of the planted acreage, approximately 85%, consists of alfalfa, grass hay, and corn. In the period from 1991 to 1998, USBR crop production and water utilization data indicate that the average irrigated acreage in the MRGCD, excluding pueblo lands, was 53,400 acres (21,600 ha) (SSPA, 2002). Analysis from 2003 through 2009 performed by this researcher indicates that roughly 50,000 acres (20,200 ha) are irrigated as non-pueblo or privately owned lands and 10,000 acres (4,000 ha) are irrigated within the six Indian Pueblos (Cochiti, San Felipe, Santo Domingo, Santa Ana, Sandia, and Isleta). Agriculture in the MRGCD is a $142 million a year industry (MRGCD, 2007). Water users in the MRGCD include large farmers, community ditch associations, six Native American pueblos, independent acequia communities and urban landscape irrigators. The MRGCD supplies water to its four divisions -- Cochiti, Albuquerque, Belen and Socorro -- through Cochiti Dam and Angostura, Isleta and San Acacia diversion weirs, respectively (Oad et al. 2009; Oad et al. 2006; Oad and Kinzli, 2006). In addition to diversions, all divisions except Cochiti receive return flow from upstream divisions.

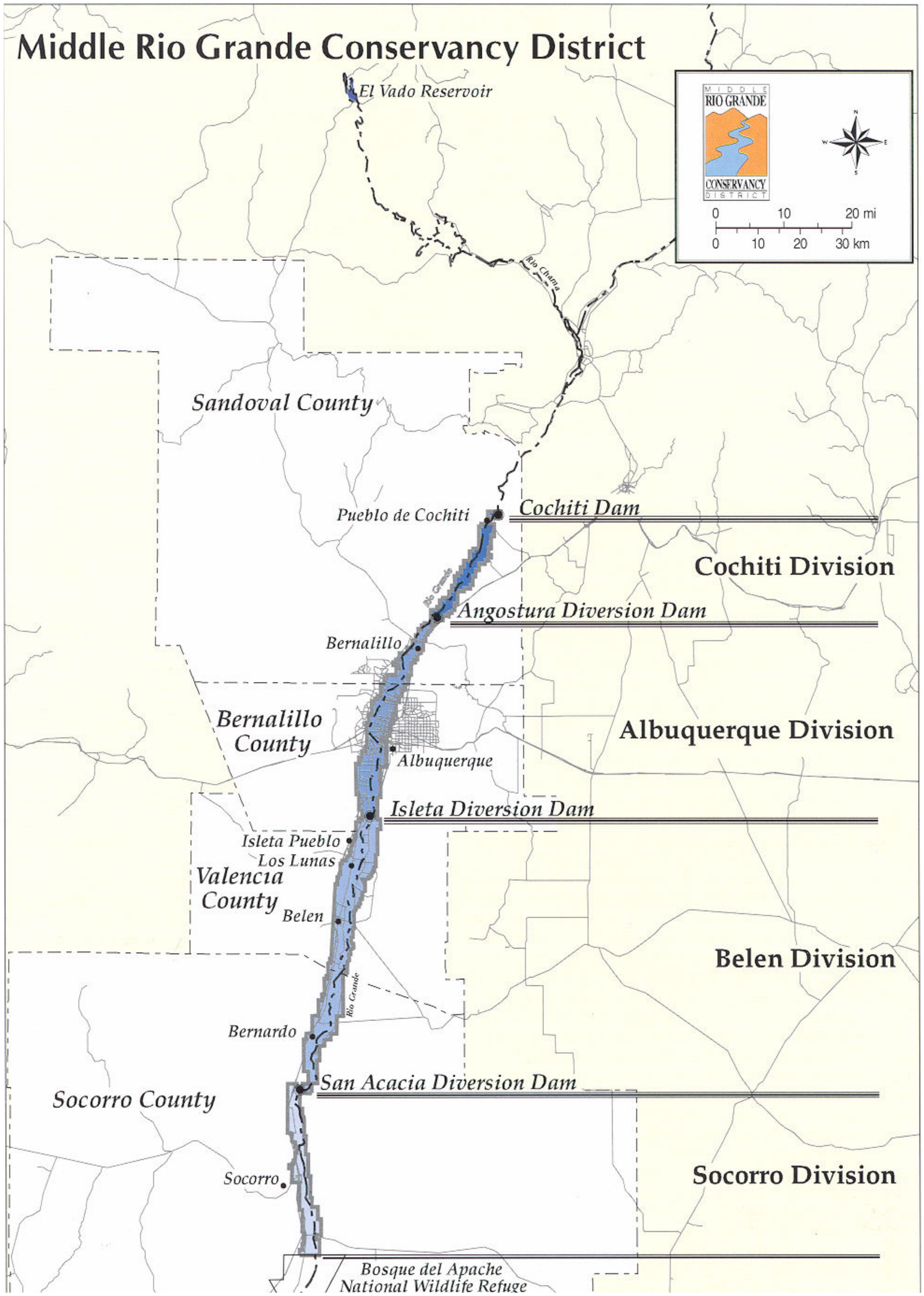


Figure 2.6: Overview Map of MRGCD (MRGCD, 2009)

Return flows are conveyed through interior and riverside drains. From the drains, excess water is diverted into main canals in the downstream divisions for reuse or eventual return to the Rio Grande. Drains were originally designed to collect excess irrigation water and drain agricultural lands, but are currently used as interceptors of return flow and as water conveyance canals that allow for interdivisional supply.

During the later part of the irrigation season, the MRGCD operates using released storage water from the high mountain reservoirs of El Vado, Heron, and Abiquiu. Water stored in these reservoirs consists of snowmelt runoff captured during the early summer months and water from the San Juan-Chama trans-mountain diversion. These reservoirs are located 98 river miles upstream and water delivery is associated with a significant time lag, which can approach seven days to reach the southern portion of the district.

The Cochiti Division consists primarily of Native American pueblo land. The pueblo and non-pueblo lands in the Cochiti Division are managed by four MRGCD ditch-riders. The non-pueblo lands in the Cochiti Division represent 723 acres. The Albuquerque Division services many small urban irrigators, but also provides irrigation water to pueblo irrigators at the northern and southern boundaries of the division. The Albuquerque Division is managed by one water master and 12 ditch-riders to oversee the complex irrigation scheme. The Albuquerque Division acreage is 6480 acres. The Belen Division is the largest in terms of overall service area with a total irrigated acreage of 28,500 acres. Irrigation in the Belen Division is comprised of large farms, pueblo irrigators, and urban water users. In Belen the MRGCD employs one water master and 11 ditch-riders. The Socorro Division consists of mostly large parcel irrigators with a total irrigated acreage of 12,000 acres. Water distribution in Socorro is straightforward when compared to the Albuquerque and Belen Division, and is managed by one water master and four ditch-riders. Water availability in Socorro can become problematic since the division depends on return flows from upstream users. Figure 2.7 displays the irrigated acreage by division from 2003 to 2009.

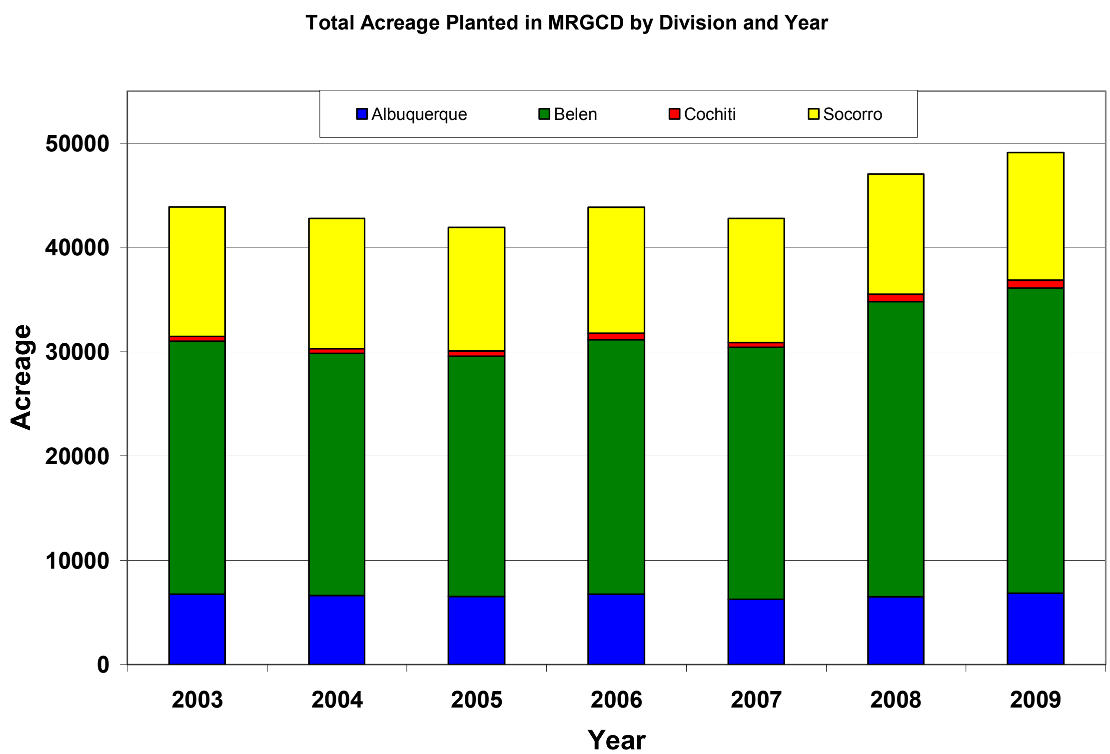


Figure 2.7: Irrigated Acreage in the MRGCD by Division from 2003 to 2009

Water in the MRGCD is delivered in hierarchical fashion; first, it is diverted from the river into a main canal, then to a secondary canal or lateral, and eventually to an acequia or small ditch. Figure 2.8 displays the organization of water delivery in the MRGCD. Conveyance canals in the MRGCD are primarily earthen canals but concrete lined canals exist in areas where bank stability and seepage are of special concern. After water is conveyed through laterals it is delivered to the farm turnouts with the aid of check structures in the lateral canals. Once water passes the farm turnout it is the responsibility of individual farmers to apply water and it is applied to fields using basin or furrow irrigation techniques.

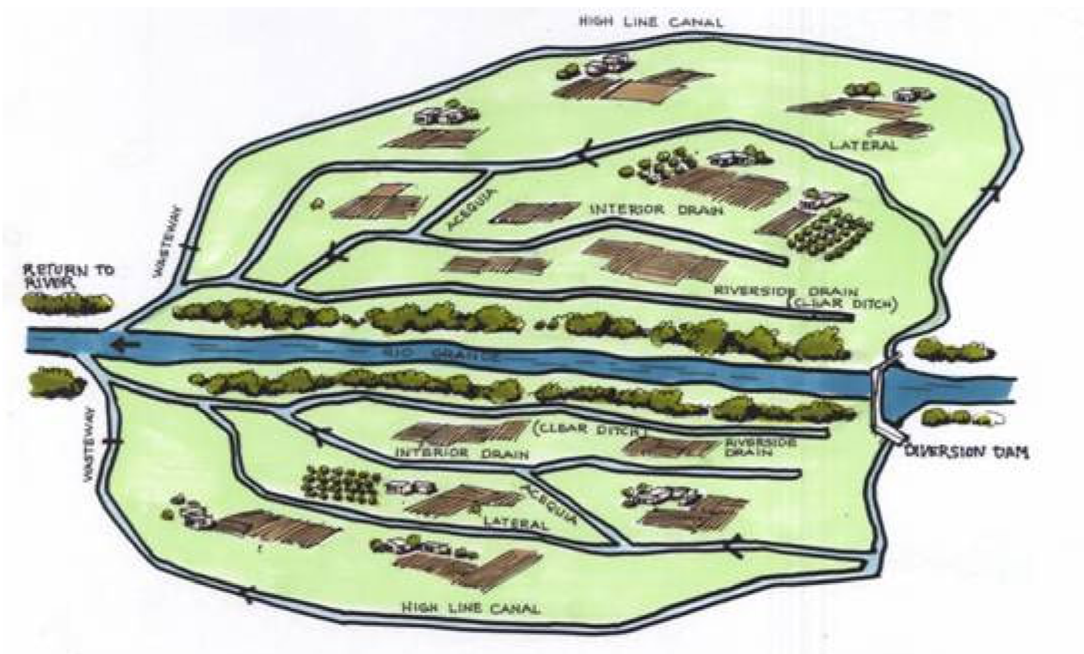


Figure 2.8: Representation of MRGCD Irrigation System (Courtesy of David Gensler and MRGCD)

2.3.4.2 Organization and Water Delivery

Water in the MRGCD is delivered to users through management and administration provided at a central office and four divisional offices. The central office in Albuquerque provides oversight of the four divisional offices and assesses service charges for water use. Each division office includes administrative, field and equipment maintenance, and water operations personnel. Water operations in each division are managed by a division manger, a water master, and ditch-riders in each division. The division managers oversee all aspects of the division, and water masters coordinate ditch-rider operations. Ditch-riders are responsible for managing water delivery in a particular service area. Ditch-riders have anywhere from 250 to 900 irrigators they are responsible for in their service area. Check structures and head gates are controlled by ditch-riders to deliver irrigation water in their service area to meet user demand. Water delivery and water use conditions are monitored by ditch-riders through the physical riding of ditches and through communication with water users. Ditch-riders generally cover all of the ditches in their service area twice a day and are in constant contact with water users via cellular phones. Ditch-riders are on call 24 hours a day to deal with emergencies and water disputes, in addition to daily operations.

Water delivery in the MRGCD is not metered at individual farm turnouts. To determine water delivery the ditch-riders estimate the time required for irrigation. The historic practice in the MRGCD was to operate main canals and laterals as full as possible throughout the entire irrigation season. This practice provided for flexible and reliable water delivery with minimal managerial and financial ramifications; also known as on-demand water delivery. On-demand or continuous water delivery, however resulted in large diversions from the Rio Grande. During the past drought years, the MRGCD has voluntarily reduced river diversions by switching to scheduled water delivery. The drawback to this approach is the increased managerial involvement and the overall cost of water delivery. To aid with the operational and managerial challenges posed by scheduled water delivery, the MRGCD has been working with Colorado State University to develop and implement a Decision Support System (DSS) to aid in facilitating scheduled water delivery. Additionally, the MRGCD has begun to replace aging water delivery infrastructure with automated control gates that make measurement and water allocations required for scheduled water delivery possible.

2.3.4.3 Definition of Water Rights

The MRGCD holds water rights and permits for irrigation, and most irrigators receive water through state permits held by the MRGCD. Since water rights are not adjudicated the delivery of water is not measured at the farm level. The MRGCD charges each water user a yearly fee of $28 per acre foot with the assumption that 3 acre-feet are applied to each acre. This use of MRGCD permits to irrigate individual lands without on farm measurements provides no incentive to conserve water. Since the application of water is not measured and water charges are not tied to actual use, the historic diversion rates of the MRGCD were high. The fact that water rights are not adjudicated in the valley also poses unique challenges to water managers. MRGCD water users do not place specific water orders, a practice that is common in almost every Western irrigation district. If water managers do not know what deliveries are required in advance, their daily operations become inefficient and wasteful because they are forced to practice on-demand water delivery.

2.4 PREVIOUS RESEARCH

Colorado State University researchers have worked with the MRGCD staff to improve irrigation efficiency since 2000. The research activities in the MRGCD were funded by the New Mexico Interstate Stream Commission (NMISC) and the Endangered Species Act Collaborative Program with the main focus of improving the water use efficiency in the MRGCD. This section describes previously completed research that set the stage for the development of the Decision Support System and implementation of scheduled water delivery.

2.4.1 Initial Reconnaissance for Efficiency Improvements

Research in the MRGCD began in 2000 when a comprehensive analysis of physical infrastructure and operational procedures was completed. Rachel Barta (Kullman), a CSU graduate student under the supervision of Dr. Ramchand Oad worked in the MRGCD for two irrigation seasons. During the first season, 2001, Kullman completed field reconnaissance and hypothesized that scheduled water delivery could be used to decrease MRGCD river diversions (Oad and Kullman, 2006; Barta, 2003). In 2002, Kullman demonstrated that scheduled water delivery could work in the MRGCD. Barta's research and thesis, *Improving Irrigation Performance in the MRGCD*, established that the MRGCD could supply its water users and their crop water demand with reduced river diversions by practicing scheduled water delivery (Oad and Kullman, 2006; Barta, 2003). In order to examine the possibility of implementing scheduled water delivery, Barta developed a methodology for formulating a water delivery schedule. The methodology developed was based on considerations of how to best allocate available water to meet crop water demands and equitably distribute water to various laterals on a main canal. In 2002 her research showed that the MRGCD could reduce river diversions by 37% and still maintain full delivery to water users using scheduled water delivery

(Oad and Kullman, 2006; Barta, 2003). Barta's initial calculations have been validated by MRGCD operations. In times when the MRGCD practiced scheduled water delivery using modern water control structures, river diversions have been reduced by about 40% (MRGCD, 2009; Gensler et al. 2009; Oad et al. 2009).

2.4.2 Development of Decision Support System for SWD

Since it was shown that scheduled water delivery would meet the goal of reducing river diversions in the MRGCD, a DSS was developed by CSU researchers. Development of the DSS began in 2004 through the work of Roy Gallea in New Mexico and programming at Colorado State University by the Integrated Decision Support Group under the supervision of Dr. Ramchand Oad (Gallea, 2005). During 2004, a preliminary version of the DSS programming was completed and initial canal schematics were developed for the Belen Division of the MRGCD. The DSS was developed to model canal networks in the MRGCD irrigation system and compute optimum water delivery options. The model structure is simple and consists of three elements: water demand, irrigation network and irrigation scheduling modules. A Graphical User Interface (GUI) is used in the DSS to link the three modules and provides a framework that enables the user to access data and output recommended irrigation schedules. The DSS solves an algorithm that minimizes water supplies needed to meet crop water demand using linear programming. During the period from 2005 to 2009 this researcher was present in New Mexico to complete the development and validation of the Decision Support System for the entire MRGCD. During the 2009 irrigation season the DSS was implemented on the

Peralta Main Canal in the Belen Division to facilitate scheduled water delivery in an area that services 7500 acres. The DSS is described in detail in Chapter 4 of this dissertation.

A literature review was also conducted to examine the principles of irrigated agriculture related to the MRGCD DSS. The principles examined include evapotranspiration, crop consumptive use, readily available moisture, crop irrigation requirement, relative water supply, and scheduled water delivery. These principles govern the use of water by agricultural crops and provide the framework for the processes modeled by the MRGCD DSS. The literature review also examines the use of decision support systems in river management and discusses several DSS models that have been used for irrigation water management. The literature review is presented in Chapter 3.

CHAPTER 3 DECISION SUPPORT SYSTEM LITERATURE REVIEW

This chapter describes soil-water plant relationships that were used in the formulation of the DSS, describes decision support systems, and gives examples of river and irrigated agricultural management using DSS models. Principles of irrigated agriculture are defined to explain the processes that the MRGCD DSS models. DSS models are explained to give background information on function, and examples of a DSS are analyzed to understand its use and applicability.

3.1 PRINCIPLES OF IRRIGATED AGRICULTURE RELATED TO DSS

The principles of irrigated agriculture are examined in the following section. The principles are examined because they govern the use of water by agricultural crops, and provide the framework for the processes modeled by the MRGCD DSS.

3.1.1 Evapotranspiration and Plant Processes

Evapotranspiration is a combination of two separate processes whereby water flows from the soil surface through evaporation and from the root zone through crop transpiration (FAO, 1998). Evaporation is the process through which liquid water is converted to water vapor at the soil surface. Transpiration is the process where by water flows from the plant leaves into the atmosphere; its state being changed from a liquid to a gaseous form. Energy is required for the evaporation of water and the net solar radiation available at the earth's surface is used to determine the resulting evaporation. As such, climatological parameters such as solar radiation, air temperature, air humidity, and wind speed are the parameters that govern evaporation (FAO, 1998). Transpiration consists of the vaporization of liquid water contained in plant tissues and the vapor removal to the atmosphere (FAO, 1998). Crops predominantly lose water through stomata (Greek for mouth), that are small openings on the leaf surface. Figure 3.1 displays a schematic of stomata.

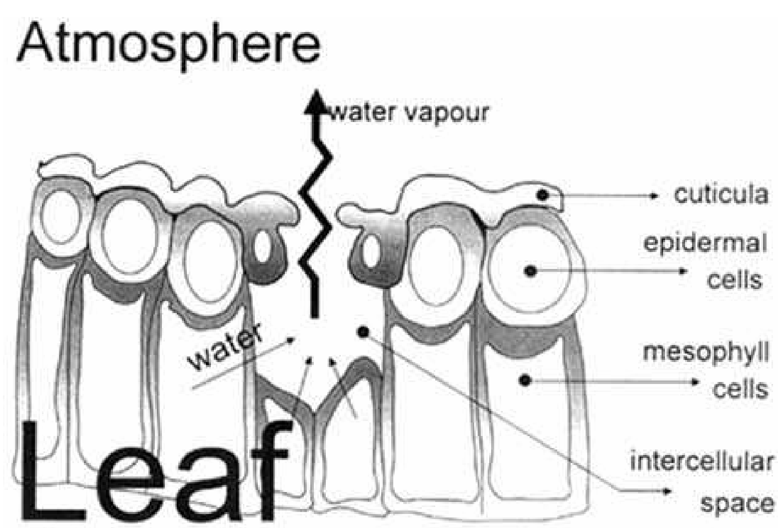


Figure 3.1: Schematic of Stomata (FAO, 1998)

Soil water, together with nutrients, is taken up by plant roots and transported through the plant. Photosynthesis is the chemical reaction where water and CO_2 are combined to produce plant carbohydrates. Since this reaction can only occur in the presence of light, the plant must open its stomata to let the light in. In the process, water in the plant tissues flows out to the atmosphere through transpiration. Nearly all water taken up by plant roots is lost to transpiration (98%), and only 2% is used within the plant itself. Transpiration from the plants depends on the total energy available for vaporization at the plant-air interface. Solar radiation, air temperature, air humidity, and wind are the driving factors affecting crop transpiration. When plants come under water stress, stomatal openings decrease in size to limit the use of water. Evaporation and transpiration occur simultaneously and the processes are linked together under the term evapotranspiration.

In order to calculate evapotranspiration for a variety of crops under different conditions a parameter termed Reference Crop Evapotranspiration (ET_o) was developed (FAO, 1998). The ET_o is affected only by climatic parameters and can be computed using weather data. The FAO recommends the Penman-Montieth method for determining ET_o because the method is widely applicable, physically based, addresses energy balances, and incorporates both physiological and aerodynamic processes (FAO, 1998). The Penman-Montieth equation for calculating reference ET on a daily basis takes the form displayed in Equations 3.1 and 3.2:

$$ET_o = \frac{\left[\frac{\Delta}{\Delta+\gamma^*}(R_n - G) + \frac{\gamma}{\Delta+\gamma^*} K_1 \frac{0.622\lambda\rho}{P} \frac{1}{r_a}(e_s - e_a)\right]}{\lambda} \qquad \textbf{(3.1)}$$

$$\gamma^* = \gamma\left(1 + \frac{r_c}{r_a}\right) \qquad \textbf{(3.2)}$$

Where:

ET_o	crop evapotranspiration (m/day)
R_n	calculated net radiation at the crop surface ($MJ/m^2 \cdot day$)
G	soil heat flux density at the soil surface ($MJ/m^2 \cdot day$)
e_s	saturation vapor pressure at 1.5 to 2 m height (Pa), calculated daily as the average of saturation vapor pressure at maximum and minimum air temperature
e_a	mean actual vapor pressure at 1.5 to 2.5 m heights (Pa)
Δ	slope of saturation vapor pressure-temperature curve ($Pa/^oC$)
γ	psychrometric constant ($Pa/^oC$)
r_a	aerodynamic resistance to sensible heat and vapor transfer (air resistance) (s/m)
r_c	surface resistance to vapor transfer (canopy resistance) (s/m)
ρ	air density (Kg/m^3)
P	mean atmospheric pressure at site elevation (Pa)
K_1	dimension coefficient ($8.64X10^4$ s/day).
λ	latent heat of vaporization (MJ/g)

Once ET_o is calculated the actual crop evapotranspiration, ET_c, can be calculated by applying a crop factor K_c. Figure 3.2 displays the calculation of ET_c.

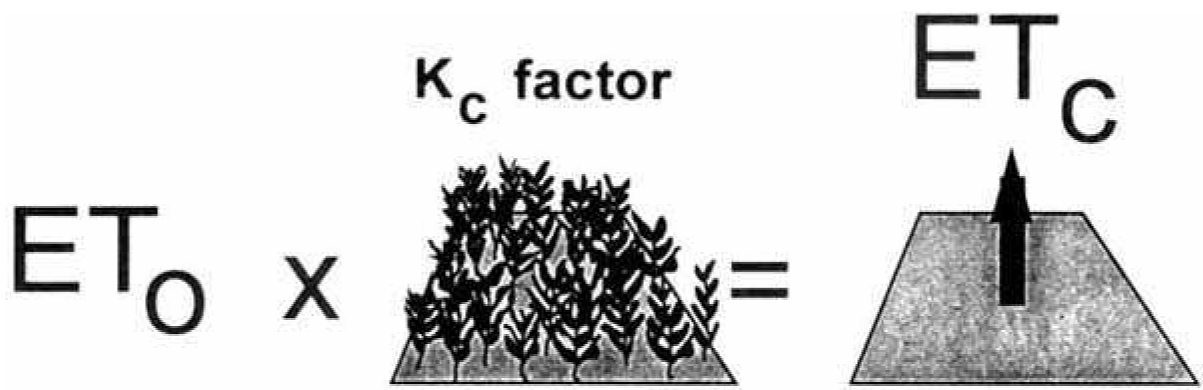


Figure 3.2: Calculation of Crop Evapotranspiration ETc (FAO, 1998)

3.1.2 Crop Consumptive Use (CU)

Crop Consumptive Use (CU) is a value delineating the water demand of a specific crop under ideal growing conditions. Crop CU is calculated by applying a crop coefficient to a calculated reference evapotranspiration, ET_o. For calculating CU the Penman-Monieth method should be used, because it accurately predicts ET_o in a wide range of locations and climates. Once ET_o is calculated the CU can be calculated by applying a crop coefficient, K_c. The crop coefficient K_c takes into account differences in resistance to transpiration, crop height, crop roughness, reflection, groundcover, and crop rooting characteristics for a variety of crop types (FAO, 1998). Multiplying the ET_o by the K_c yields a CU that is applicable to crops grown in large fields under optimum soil water conditions (FAO, 1998).

3.1.3 Crop Coefficients (K_c) Using Growing Degree Days

In order to account for the growth of crops during an irrigation season Growing Degree Days (GDD) are commonly used to calculate K_c. GDD are an accumulation of heat units needed for plant growth and development (King et al. 2000). From temperature data (C^o) GDD are determined using the method displayed in Equation 3.3.

$$GDD = \frac{(DailyMaxTemp + DailyMinTemp)}{2} - BaseTemperature \quad \textbf{(3.3)}$$

GDD accumulate throughout an irrigation season and a K_c curve for a certain crop is determined experimentally using lysimeters on a regional basis (King et al. 2000).

From experimentally developed curves, functions can be developed that predict K_c using GDD. It is important to emphasize that prediction equations for K_c are developed in the region for which they are to be used.

3.1.4 Readily Available Moisture (RAM)

Readily Available Moisture (RAM) is a term developed to characterize the water stored in soils that is readily accessible to crops. In order to properly define RAM it is necessary to understand the soil moisture content variables that affect the RAM.

Saturation: Saturation is defined as the state of soil moisture content when all of the pores in a soil are filled with water. Mathematically, saturation is defined as the volume of water divided by the volume of voids; therefore, when all the voids are filled, a soil is completely saturated.

Field Capacity: The field capacity is defined as the water content in an agricultural soil when gravitational drainage ceases. Field capacity is essentially the volumetric water content in a soil two to three days after a complete irrigation event (Podmore, 2005). In most soils, soil-water potential at field capacity is one third of atmospheric pressure.

Critical Point: The critical point is defined as the volumetric water content when crop yields decrease due to induced water stress. The critical point depends on crop type and is related directly to the ability of the plant to extract water from the soil. Once the critical point is exceeded, yields decrease as plants close their stomatal apertures to conserve water (Podmore, 2005).

Permanent Wilting Point: The wilting point, or more accurately the permanent wilting point, is the volumetric water content of the soil at which a plant can no longer extract any water (Podmore, 2005). When the wilting point is reached or exceeded the crop will be stressed. The crop may recover with irrigation but the yield will be decreased. The permanent wilting point depends on the crop type, the stage of growth, and the soil-water potential.

Total Available Water (TAW): The Total Available Water (TAW) is defined as the difference between the field capacity and the permanent wilting point (Podmore, 2005). The TAW represents the amount of water that is theoretically available for plant extraction.

Readily Available Moisture (RAM): The RAM is defined as a certain fraction of TAW. RAM represents the fraction of TAW under which plants can extract water without experiencing any stress. The critical point is defined by using a Management Allowed Depletion Factor (MAD) that prevents crops from going into water stress. MAD values are crop specific, because some crops can withstand water stress better than others. In general, MAD values range between 30% and 60% (FAO, 1998). RAM is calculated by multiplying the MAD by the TAW. Figure 3.3 displays a schematic of RAM and Soil Moisture Content.

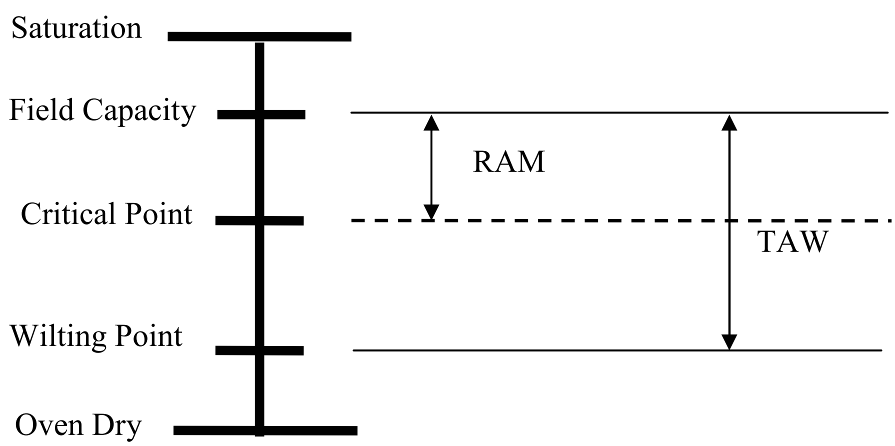


Figure 3.3: Schematic of RAM and Soil Moisture Content

3.1.5 Crop Irrigation Requirement

Crop Irrigation Requirement (CIR) is defined as the Consumptive Use (CU) of the crops minus any rainfall that contributes to meeting the CU. Using CIR for irrigation is critical, because over-irrigation would occur if the CU was used and rainfall was neglected. Effective precipitation used to calculate CIR is generally calculated using the Soil Conservation Service Method (NMISC, 2006). This method takes into account that slow soaking rains are more easily absorbed and available for crop use than quick heavy downpours that result in large amounts of surface runoff.

3.1.6 Relative Water Supply (RWS)

The concept of Relative Water Supply (RWS) relates available water supply, demand for water use, and the management intensity in an irrigation system (Oad and

Podmore, 1989). In general, this concept relates changes in water supply availability relative to demand to the level of management intensity and control. Relative water supply is graphically displayed in Figure 3.4. Equation 3.4 displays the mathematical expression of RWS (Oad and Levine, 1985).

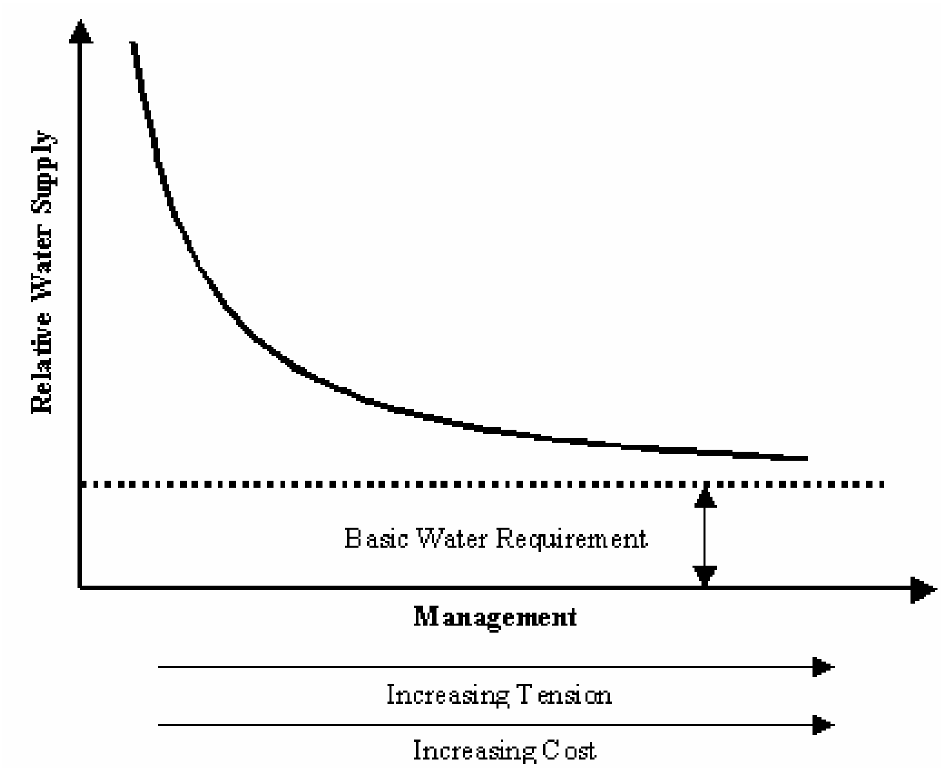


Figure 3.4: Relative Water Supply Concept (Barta, 2003)

$$RWS = \frac{WaterSupply}{DemandforWater} = \frac{IrrigationDeliveries + Rain}{Evapotranspiration + DeepPercolation \,\&\, Seepage} \qquad \textbf{(3.4)}$$

The RWS can be calculated on any unit of an irrigation system including a farm, an irrigation service canal or an entire irrigation district. In an irrigation system the decrease of water delivery and rainfall result in a lower RWS. A lower RWS results in tighter and more stringent management requirements to equitably distribute water to users. Tighter management in an irrigation system consequently leads to an overall higher cost of water delivery.

RWS is similar to the supply and demand concept associated with capitalism. If supply exceeds demand, cost goes down and competition decreases. As demand exceeds supply, cost increases significantly and competition for a limited resource is exacerbated. RWS has been used to explain how management intensity changes according to variable water supply conditions. Oad and Podmore (1989) found that irrigation systems in Central Java, Indonesia, manage the cost of operation according to changes in water supply. During the wet season when RWS is high, water flows in irrigation canals continuously and farmers can irrigate at their own leisure and management costs are low. During the dry season RWS decreases significantly and the management required for equitable water distribution increases. This increase in management results in a higher cost of water delivery.

In the MRGCD historical water distribution consisted of running canals and laterals near capacity. This provided for a high RWS that allowed for low intensity management and low cost. To lower the RWS, and improve water use efficiency, the MRGCD has opted to use scheduled water delivery for water distribution. With a lower RWS, the management and cost of water delivery have increased. In order to equitably distribute the water supply under low RWS, the MRGCD has opted to develop and implement the MRGCD DSS to assist with increased management intensity.

3.1.7 Scheduled Water Delivery (SWD)

Scheduled Water Delivery (SWD) is used in irrigation systems worldwide to improve water delivery and to support water conservation. When SWD is used, lateral canals receive water from the main canal according to their need for water, allowing water use in some laterals while others are closed. In addition to this water scheduling among laterals, there can be scheduling within laterals whereby water use is distributed in turns among farm turnouts or check structures along a lateral. By distributing water among users in a systematic fashion based on crop demand, an irrigation district can decrease water diversions and still meet crop water use requirements. A well-managed program of scheduled water delivery is able to fulfill seasonal crop water requirements in a timely manner, but generally requires less water than continuous water delivery.

3.2 DEFINING A DECISION SUPPORT SYSTEM

A DSS combines intellectual resources of individuals with the capabilities of computers to improve the quality of decision-making. A DSS is a logical arrangement of information including engineering models, field data, GIS, graphical user interfaces, and is used by managers to make informed decisions.

3.3 RIVER MANAGEMENT WITH DSS MODELS

Decision support systems have found implementation throughout the American West and are mostly used to regulate river flow. Decision support systems on the river level are linked to gauging stations and are used to administer water rights at diversions points. Three past projects are mentioned in this section to show the successful use of DSS models in river management.

3.3.1 Colorado River DSS (CRDSS)

The CRDSS was developed to manage the waters of the Colorado River. The main goal of the CRDSS is to develop credible information on which to base informed decisions concerning management of Colorado River water. The CRDSS consists of databases and models that provide improved data and decision making capabilities for many critical Colorado River planning, administrative, and operational issues (CDSS, 2005). The CRDSS aids in managing instream flow required by the endangered Colorado pikeminnow (Ptychocheilus lucius) and razorback sucker (Xyrauchen texanus).

3.3.2 Upper Rio Grande DSS (RGDSS)

The RGDSS is a water management system to assist in making informed decisions regarding historic and future use of water in the Upper Rio Grande basin (Gallea, 2005). The RGDSS is comprised of water resource databases, models, data viewing and visualization tools, and is compatible with the already formulated CRDSS.

3.3.3 South Platte DSS (SPDSS)

A DSS has been developed for the South Platte River basin in northern Colorado by the Integrated Decision Support Group (IDS) at Colorado State University. The South Platte DSS includes computer systems that manage large amounts of data and provides information in a comprehensive and interdisciplinary manner for managers to make informed decisions (IDS, 2006). The SPDSS is the third DSS developed by the State of Colorado. The development of the SPDSS built upon the experience, databases, tools, and models already completed for the CRDSS and RGDSS. The main purpose of the SPDSS is to manage and preserve water resources in the North and South Platte River basins (CWC, 2001). The SPDSS is the most effective data management and information exchange tool in the region (CWRRI, 1995).

3.4 IRRIGATION WATER DELIVERY MANAGEMENT WITH DSS MODELS

Although decision support systems have proved their worth in river management, few have been implemented for modeling irrigation canals and laterals. In irrigation systems a DSS can organize information about water demand in a service area and then schedule available water supplies to efficiently fulfill the demand.

The conceptual problem addressed by a DSS for an irrigation system is then a question of how best to route water supply in a main canal to its laterals so that the required water diversion is minimized. The desirable solution to this problem should be demand-driven, in the sense that it should be based on a realistic calculation of water demand. The water demand in a lateral canal service area, or for an irrigated parcel, can be predicted throughout the season through analysis of information on the irrigated area, crop type, and soil characteristics. Important demand concepts are: when is water supply needed to meet crop demand (Irrigation Timing), how long is the water supply needed during an irrigation event (Irrigation Duration), and how often must irrigation events occur for a given service area (Frequency of Irrigation). The MRGCD DSS was developed using the above mentioned concepts of irrigation timing, irrigation duration, and frequency of irrigation. The following subsections describe two models that have been developed for irrigation systems to prove that a DSS can model irrigation systems and be used to reduce river diversions.

3.4.1 DSS for the Jingtai Chuan Irrigation Scheme (DSSJC)

The Jingtai Chuan Irrigation Scheme (JCIS) is located in the Gansu Province of Northwest China. The average annual rainfall is 7.9 inches (201 mm) while the average evapotranspirtaion is 90 inches (2308 mm) (Gao, 1999). The irrigated area in the JCIS consists of 135, 265 acres (54,740 ha) (Gao, 1999). Due to a complicated system of irrigation canals, farmers at the head of canals always received water, while downstream users were rarely provided with their share of irrigation water. To institute equitable water distribution, the China Institute of Water Resources and Hydropower Research developed the DSSJC.

The DSSJC incorporates data regarding water resources, climate conditions, water requirements and water distribution to allow for informed management decisions (Gao, 1999). Due to the changing nature of data during an irrigation season, the DSSJC was developed with the feature of collecting and processing information dynamically. The structure of the DSSJC is comprised of four main elements: (1) The information base that includes water resources, climate data, soil data and related agricultural production info; (2) The water application base that includes crop water requirements and water application; (3) The model base that includes the crop water requirement model, the irrigation scheduling model and the canal simulation model; and (4) The knowledge base that includes operator input based on experiences with irrigation water management (Gao, 1999). Figure 3.5 displays the structure of the DSSJC.

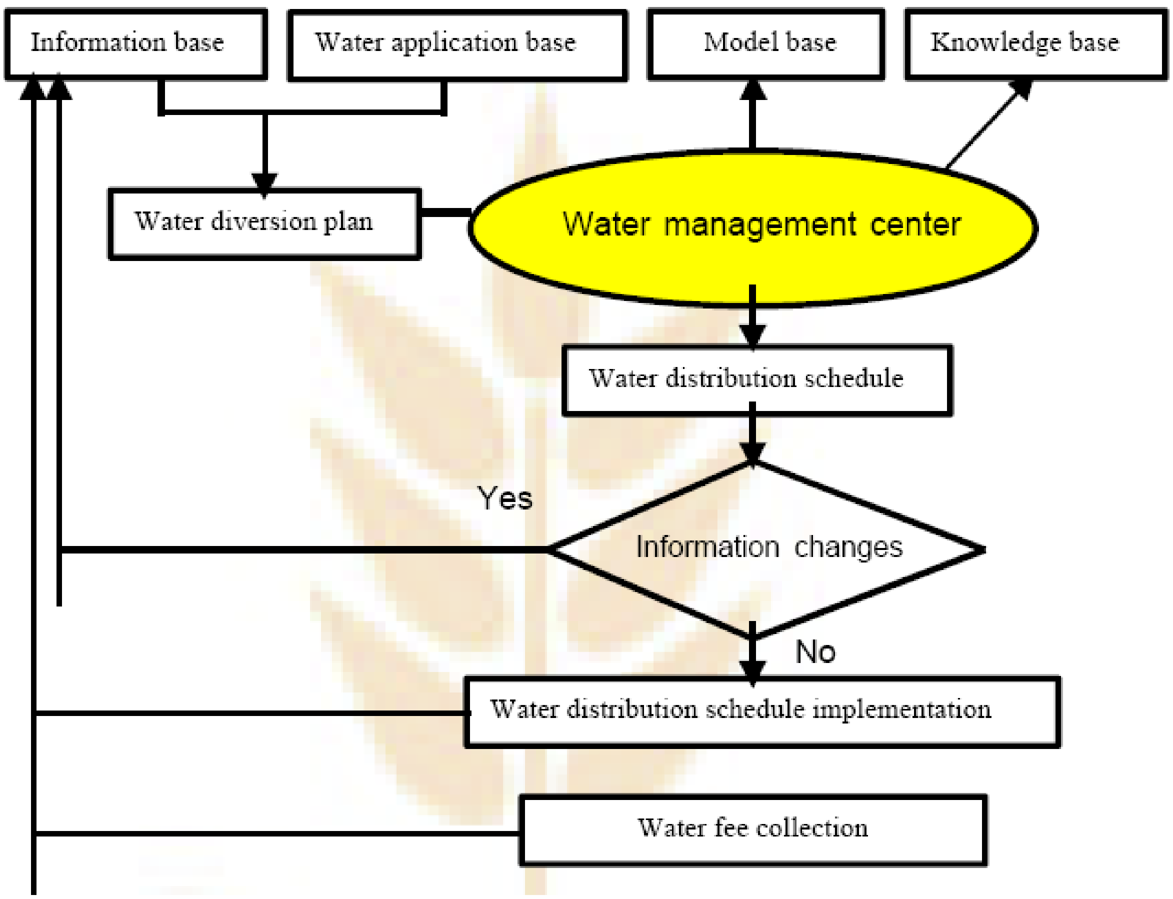


Figure 3.5: Structure of the DSSJC (Gao, 1999)

The DSSJC was designed with the main goal of improving water management through solving the conflict between water supply and demand. To insure that management was improved the DSSJC was developed with the following modules:

Basic Data Module: The basic data module consist of data and information related to water diversion and distribution, such as canal features of the irrigation district, climate, hydrology, irrigation areas, water users, crops patterns and economic conditions (Gao, 1999).

Water Application Module: The water application module collects and calculates water application volumes from all users. It also calculates the water volumes and rate of discharge of different canals. Water users can apply water according to their needs (Gao, 1999).

Water Planning Module: The water planning module is developed to make water diversion and water distribution schedules. According to the required water application, water supply, and canal capacity, water diversion plans are developed. If changes occur during the irrigation season, the module can modify the water diversion and distribution schedule (Gao, 1999).

Water Fee Management Module: The function of the module is to calculate water volumes, water fees for all users, and to record water fee collection status.

Statistic Module: The statistic module was designed to record the water distribution and irrigation process. It can show the irrigated areas and irrigation schedule, it and provides useful information for future irrigation water management (Gao, 1999).

Communication Module: The communication module is used to coordinate communication between the water management center and water management stations, as well as among users (Gao, 1999).

Print and Preview Module: The print and preview module was designed to output the model results by tables or figures (Gao, 1999).

The DSSJC has been in use since 1996. Significant economic and social benefits have been achieved due to the improvement of water management in the irrigation district by adopting the system (Gao, 1999). Both water use efficiency and water distribution uniformity have been increased since the application of the system (Gao, 1999).

3.4.2 Scheme Irrigation Management Information System (SIMIS)

SIMIS is a decision support system that has been developed for the purpose of facilitating the management tasks in an irrigation scheme (FAO, 2006). SIMIS was developed to furnish a set of programs that could be used in most irrigation systems, leaving aside irrigation schemes that are too specific for general modeling (FAO, 2006). SIMIS was developed to fulfill the need for irrigation data management on a large scale. Proper daily management of large amounts of irrigation data plays an essential role in water conservation, because a significant amount of diverted water is lost in conveyance and distribution (FAO, 2006). SIMIS was developed to deal with irrigation schemes in developing countries where water is conveyed in open channels and water application consist of surface irrigation (FAO, 2006).

SIMIS is structured to be versatile and adaptable to local conditions, and has a multi-lingual option for international applications. SIMIS is based on the use of two main modules: a Project Data Module and a Management Module (FAO, 1006).

Project Data Module: The Project Data Module consists of nine separate sub-modules in which a user can input new data, modify existing data, and retrieve data for informed decision making (FAO, 2006). The nine sub-modules are listed below:

- Climatic Stations
- Climatic Data
- Soil Data
- Crop Data
- Irrigation Network
- Sectorization Data
- Land Tenure
- Land Use
- Maintenance Data

Management Module: The management module is divided into water management and financial management. The management module uses the project data module to calculate the following:

- Crop Water Requirements
- Irrigation Plans
- Water Delivery Schedules
- Accounting Information
- Water Fees
- Performance Indicators
- Required Maintenance Activities

SIMIS allows for the management of an entire irrigation scheme through the calculation of the above mentioned parameters. In order to use SIMIS, training workshops are employed that allow a user to become familiar with the software in 20-30 hours (FAO, 2006). SIMIS is limited by the fact that structure cannot be modified and that it only allows for one water source per system. SIMIS could therefore not be implemented in the MRGCD, because each division has multiple diversions from the Rio Grande.

In 1994, SIMIS was implemented under a pilot program in the Mendoza River Valley of Argentina. SIMIS was applied to the Matriz Gil Secondary canal to analyze the advantages of using a DSS for irrigation management (FAO, 1994). SIMIS was shown to be advantageous in processing and storing large amounts of financial and irrigation data. Through the compilation of data, SIMIS is able to maximize production and minimize environmental degradation (FAO, 1994). In the Matriz Gil Secondary Canal, SIMIS was able to identify that irrigation efficiency was 34% in 1994 (FAO,1994). Through the use of SIMIS, physical and operational improvements were identified that could eventually lead to a much higher efficiency in the Matriz Gil Secondary Canal (FAO ,1994).

CHAPTER 4 MRGCD DSS FOR SCHEDULED WATER DELIVERY

This chapter examines the framework of the developed MRGCD DSS. The model structure is described along with the methods for modeling agricultural processes. The model programming is also delineated so that a complete overall understanding of the MRGCD DSS can be gained.

4.1 CONCEPTUAL DESCRIPTION AND FRAMEWORK

The DSS has been formulated to model and manage water delivery in the MRGCD. The DSS was designed to optimize water scheduling and delivery to meet crop water demand, and, specifically, to aid in the implementation of scheduled water delivery (Oad et al. 2009; NMISC, 2006). A journal article detailing the DSS developed for the MRGCD is included in Appendix B.

The DSS consists of three elements, or modules:

- A water demand module that calculates crop consumptive use and soil moisture storage, aggregated by lateral service area;
- A water supply network module that represents the layout of the conveyance system, main canal inflow, conveyance system physical properties, and the relative location of diversions for lateral service area; and,

- A scheduling module that routes water through the supply network to meet irrigation demand using a mass-balance approach and based on a ranking system that depends on the existing water deficit in the root-zone.

A Graphical User Interface (GUI) was designed to link the three modules of the DSS together allowing users to access data and output for the system. A schematic of the three modules and the way that they relate within the DSS framework is shown in Figure 4.1. Figure 4.2 displays a simplified view of the DSS. GIS information and data obtained from the MRGCD were used to develop input for both the water demand and the supply network modules. Some of the input is directly linked through the GUI and some is handled externally (NMISC, 2006).

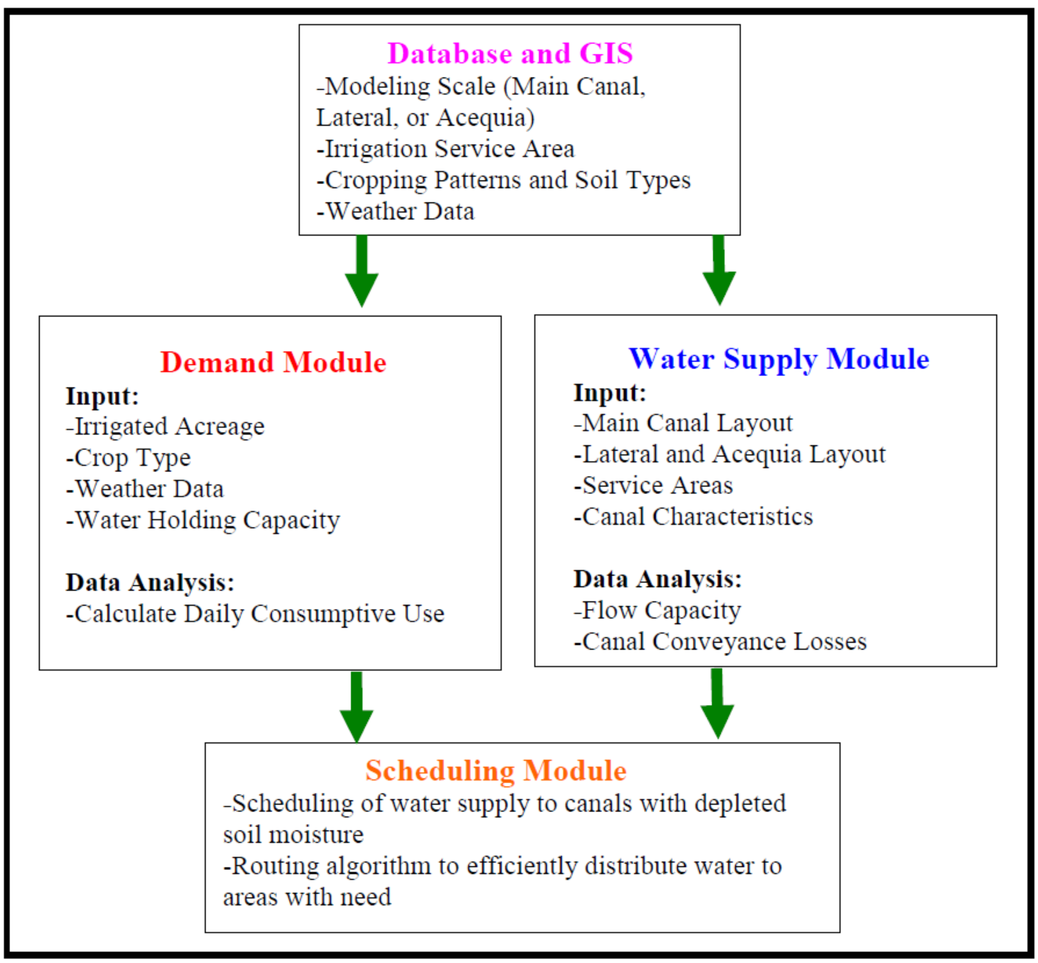


Figure 4.1: DSS Model Structure Showing Modules

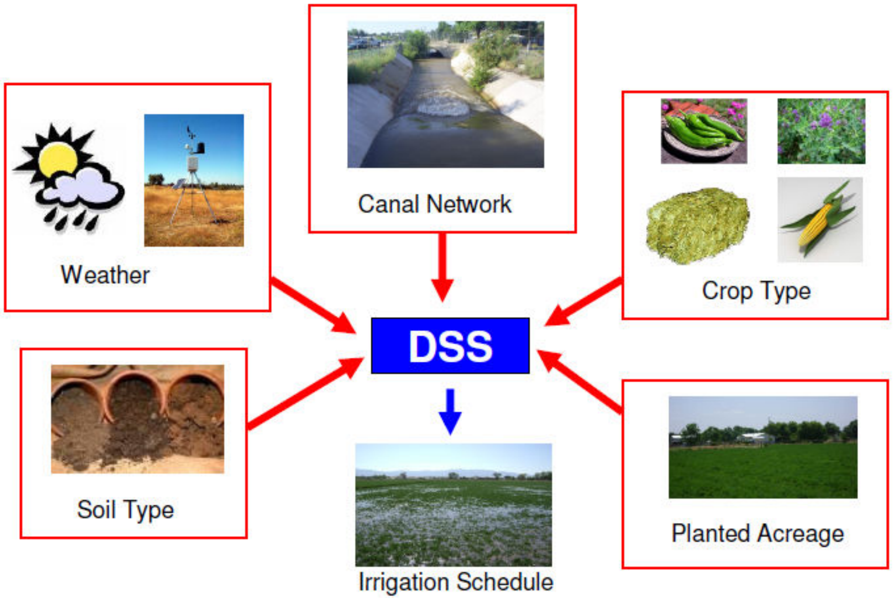


Figure 4.2: Simplified View of the DSS

The DSS has two modes of operation: planning mode and operation mode. In planning mode, the user inputs an anticipated cropping pattern for the season and other related data, and the model calculates the required main canal diversions as a function of time based on the calculated demand. In operation mode, the user inputs the available main canal flows, and the model recommends a water delivery schedule for the lateral canal service areas within the main canal that optimizes the use of available water (Oad et al. 2009; NMISC, 2006).

4.2 MODEL STRUCTURE

The MRGCD DSS was developed using three modules. The three modules that comprise the MRGCD DSS are the water demand module, the supply network module, and the irrigation scheduling module. The following subsections describe the three modules in detail.

4.2.1 Water Demand Module

The water demand module of the MRGCD DSS is implemented through the Integrated Decision Support Consumptive Use (IDSCU) model code or the ET Toolbox. The IDSCU model was developed over a period of years by Colorado State University. The IDSCU code consists of a GUI written in Visual C++ and program calculations implemented with FORTRAN (Oad et al. 2009; NMISC, 2006). The ET Toolbox was developed specifically for the Middle Rio Grande and calculates the crop consumptive use using a system of weather stations throughout the valley. Using either the IDSCU or the ET Toolbox, the following variables are determined in the water demand module:

- Crop consumptive use (CU);
- Crop irrigation requirement (CIR); and,
- Readily available (soil) moisture (RAM), as a capacity.

CIR and RAM as a capacity, are used in the supply network module. Required data for the water demand module, the source of these data, and the spatial unit for which the information is aggregated, are shown in Table 4.1.

Table 4.1: Required Data for Water Demand Module (NMISC, 2006)

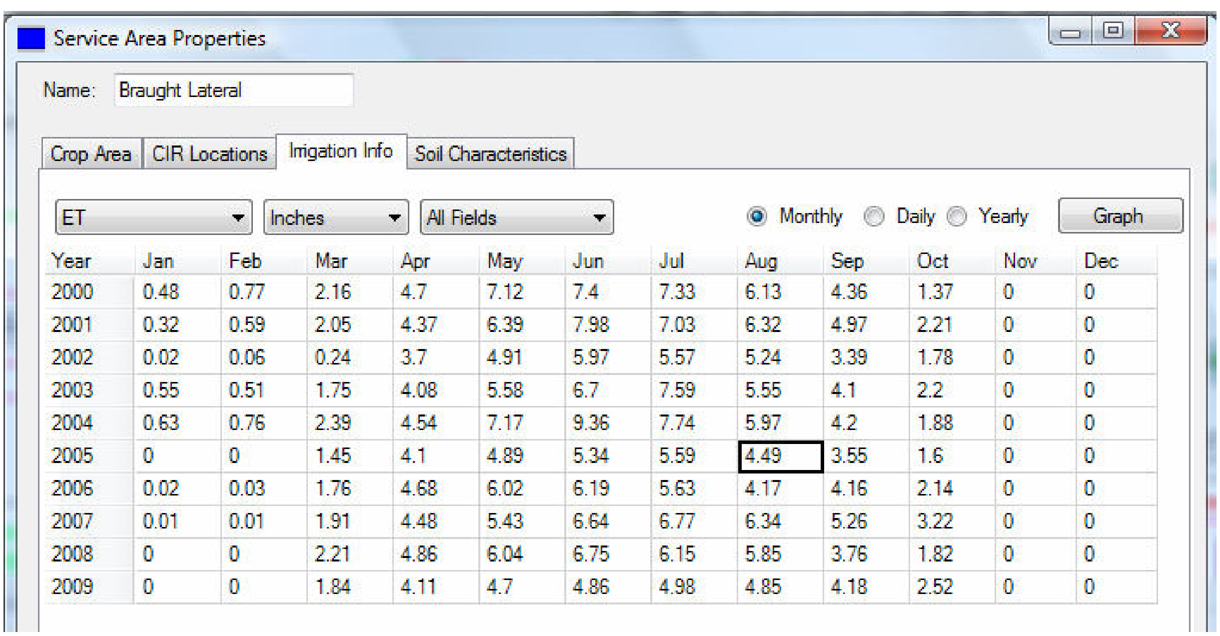
Data for Water Demand Module		
Required data	**Source of data**	**Mgmt. level in irrigation system**
Service area and irrigated area	MRGCD GIS database: legal parcel delineation, lateral service area boundaries	Sample lateral canals
Cropping patterns	MRGCD database, field observation	Cumulative for lateral service areas
Soil: Available water holding capacity (*AWC*)	NRCS SSURGO Database	Lateral service areas
Weather data, rainfall, crop coefficients, planting / harvest dates	USBR ET Toolbox, Penman-Montieth Equation	Averages for lateral service areas
Other variables: root zone depth and management allowable depletion	ASCE Manual 70 (FAO. 1998)	Averages for lateral service areas

4.2.1.1 Crop Consumptive Use (CU)

The Penman-Monteith method suggested by FAO is used to determine the crop consumptive use for the system when using the IDSCU. The Penman-Monteith equation is discussed in detail in Chapter 3. When using the IDSCU, weather data required for the calculation are obtained from the USBR ET Toolbox (USBR, 2003). The USBR ET Toolbox obtains weather data from 16 weather stations throughout the MRG Valley. In the water demand module, crop coefficients using growing degree days are combined with the Penman-Monteith based ET to obtain a consumptive use for each crop type throughout the growing season. Crop coefficients using growing degree days were obtained from the New Mexico Climate Center and are based on work done by (King et al. 2000). The water demand module performs calculations to obtain a spatially-averaged CU at the lateral service area level using the distribution of crop types within each service area. When the ET Toolbox is used in the demand module, the consumptive use is already calculated within the ET Toolbox using grid cells throughout the valley.

4.2.1.2 Crop Irrigation Requirement (CIR)

The Penman-Monteith-based CU is adjusted to account for effective precipitation, and is used to obtain a CIR for each lateral service area. Effective precipitation is calculated according to the Soil Conservation Service Method (USDA, 1967), and is subtracted from the Penman-Monteith-based CU. The CIR is calculated on a daily basis, corresponding to the water needed to directly satisfy crop needs for all acres in a lateral service area. The CIR for each lateral is subsequently passed to the supply network module, where it is divided by an efficiency factor to obtain a lateral delivery requirement or LDR (NMISC, 2006). Figure 4.3 provides a snapshot of the demand module interface and shows the ET for a given service area by month. From this interface supporting data for the calculations can be accessed, reviewed and edited.



Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	0.48	0.77	2.16	4.7	7.12	7.4	7.33	6.13	4.36	1.37	0	0
2001	0.32	0.59	2.05	4.37	6.39	7.98	7.03	6.32	4.97	2.21	0	0
2002	0.02	0.06	0.24	3.7	4.91	5.97	5.57	5.24	3.39	1.78	0	0
2003	0.55	0.51	1.75	4.08	5.58	6.7	7.59	5.55	4.1	2.2	0	0
2004	0.63	0.76	2.39	4.54	7.17	9.36	7.74	5.97	4.2	1.88	0	0
2005	0	0	1.45	4.1	4.89	5.34	5.59	4.49	3.55	1.6	0	0
2006	0.02	0.03	1.76	4.68	6.02	6.19	5.63	4.17	4.16	2.14	0	0
2007	0.01	0.01	1.91	4.48	5.43	6.64	6.77	6.34	5.26	3.22	0	0
2008	0	0	2.21	4.86	6.04	6.75	6.15	5.85	3.76	1.82	0	0
2009	0	0	1.84	4.11	4.7	4.86	4.98	4.85	4.18	2.52	0	0

Figure 4.3: Demand Module User Interface

4.2.1.3 Readily Available Soil Moisture (RAM)

RAM is calculated in the MRGCD DSS according to the process delineated in Chapter 3. RAM is determined by first calculating the total available water (TAW) per unit area, which is the available water-holding capacity (AWC) for a given soil type, multiplied by the root-zone depth (Figure 3.3). The calculation of TAW is displayed in Equation 4.1 (Oad et al. 2009; NMISC, 2006).

$$\text{TAW} = \text{AWC} * \text{root zone depth} \qquad \textbf{(4.1)}$$

Once the TAW is calculated, a management allowed depletion factor (MAD) for each crop type is applied to determine the RAM. The values employed for MAD in the Water Demand Module are crop specific and range from 30% to 60% (NMISC, 2006; FAO, 1998). RAM is calculated using Equation 4.2

$$\text{RAM} = \text{MAD} * \text{TAW} \qquad \textbf{(4.2)}$$

Based on acreage, crop type, and soil type within each lateral service area, a value for RAM is calculated. The RAM calculated in this context represents a storage capacity to be filled and depleted over several irrigation cycles during the course of the irrigation season (NMISC, 2006). During each irrigation event, it is expected that an amount of water equal to the RAM will be stored in soils. Then, as crops utilize water, the RAM will become depleted (Oad et al. 2009; NMISC, 2006).

4.2.2 Supply Network Module

The supply network module consists of data relating to water supply, water demand, and physical information relating to the conveyance network. It represents the layout of the conveyance system, its physical properties, and the relative location of diversions from the network to individual lateral service areas (Oad et al. 2009; NMISC, 2006). The layout of the conveyance system is specified through a user-designed link-node network. Through the DSS GUI, a user can drag and drop in different types of nodes such as inflows, demands, and return flow nodes into the program (NMISC, 2006). Developing the link-node network is straightforward and can be completed by ditch-riders and water master after some short training. The link-node network represents the connections between canals or laterals and water demands for each service area. The GUI also contains information on ditch-rider service area, and includes photographs and locations of all major water control structures. Figure 4.4 provides a view of the link-node network.

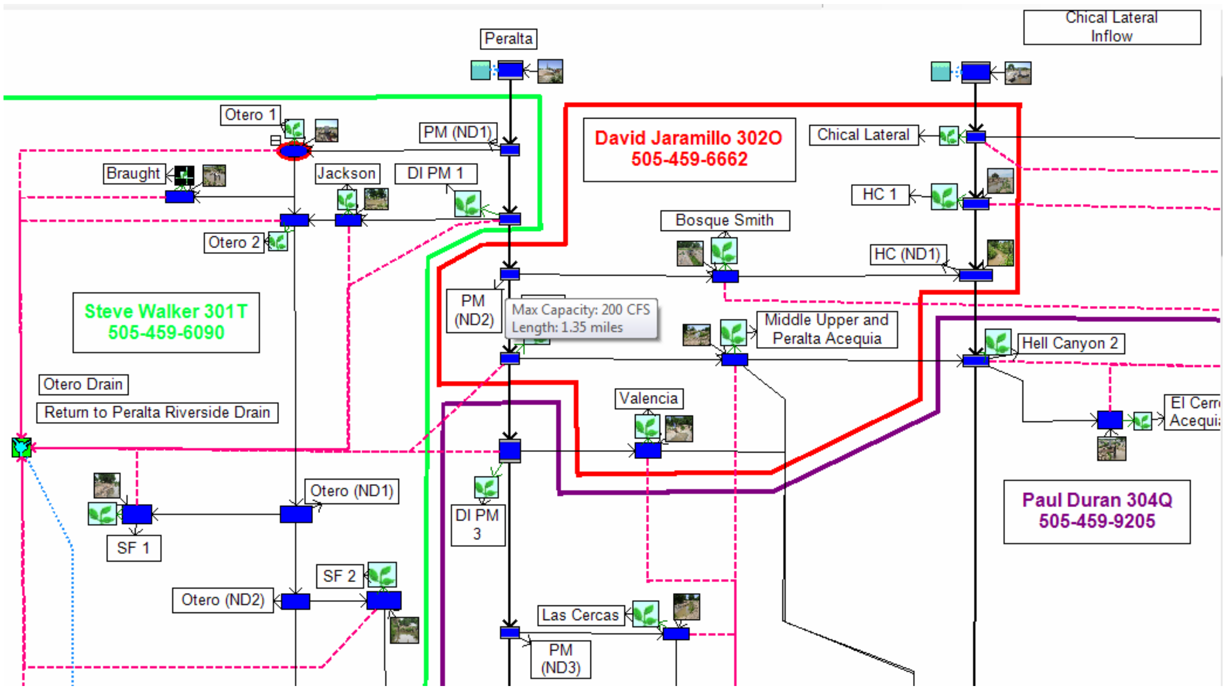


Figure 4.4: DSS Link-Node Network

The supply network module obtains the CIR and the RAM from the water demand module, and then associates these parameters with a demand node on the link-node network (Oad et al. 2009; NMISC, 2006). An efficiency factor is applied to the CIR to account for on-farm application efficiency and to account for conveyance losses within the service area. This results in a lateral delivery requirement (LDR) that applies to all acreage served by a given lateral. The efficiency factor can be specified by the user for each lateral service area (NMISC, 2006).

The link-node network representing the layout of the conveyance system within the supply network module consists of inflow nodes, stream nodes, and return-flow nodes, connected by links that represent canals and laterals (NMISC, 2006). Inflow nodes contain information about inflow volume. The user may either type the inflow values into the inflow node GUI, or import them from an inflow table. Inflow values in the GUI are displayed in Figure 4.5.

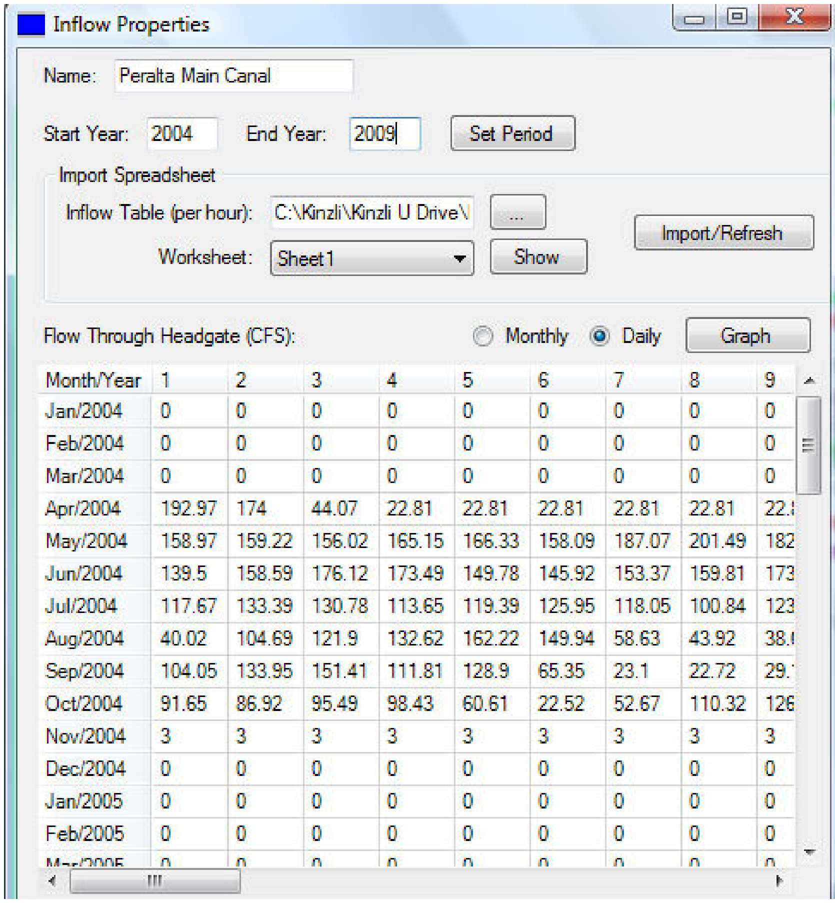


Figure 4.5: Example GUI for Inflow Node

Stream nodes require the user to provide information about individual lateral service areas, including turnout capacity, the number of days needed to completely irrigate the service area, the lateral service area efficiency factor, which days of the week the service area can be irrigated, the minimum flow required in the canal on a daily basis, and to which "sub-system" a given stream segment belongs (NMISC, 2006). Sub-systems are used to preferentially rank laterals that should be irrigated together. The GUI for stream nodes is displayed in Figure 4.6.

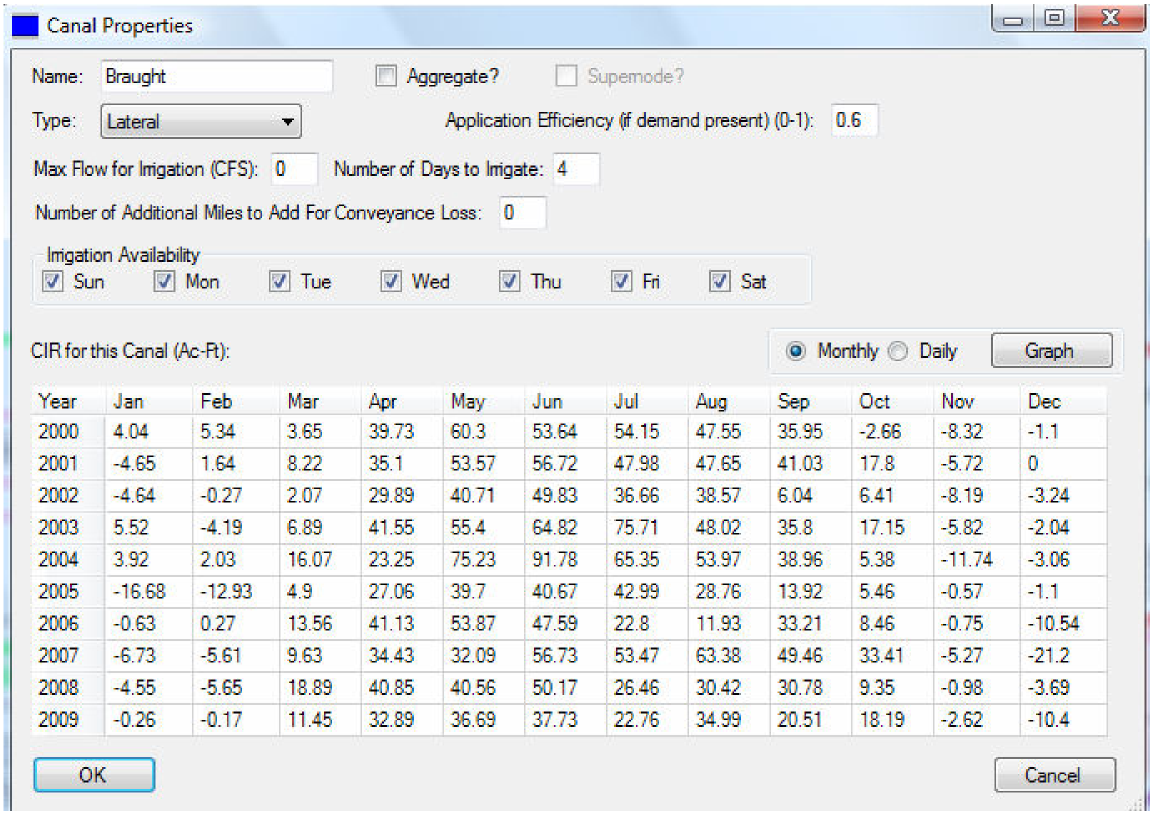


Figure 4.6: Example GUI for Stream Node (NMISC, 2006)

Return flow nodes are used to capture and route drain flow. The percentage of water applied to farms that can be captured by drains is set by the user for the entire project. Each drain has a daily schedule that indicates how much of that return flow is available as inflow in the successive days (NMISC, 2006). The model uses the return flow availability distribution displayed in Figure 4.7.

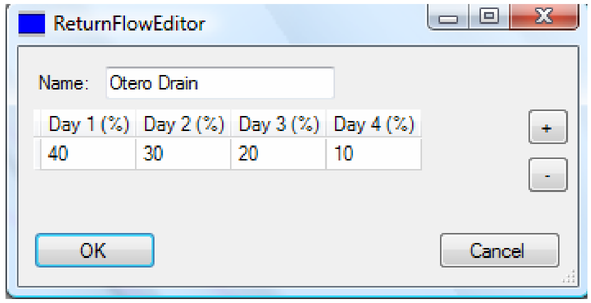
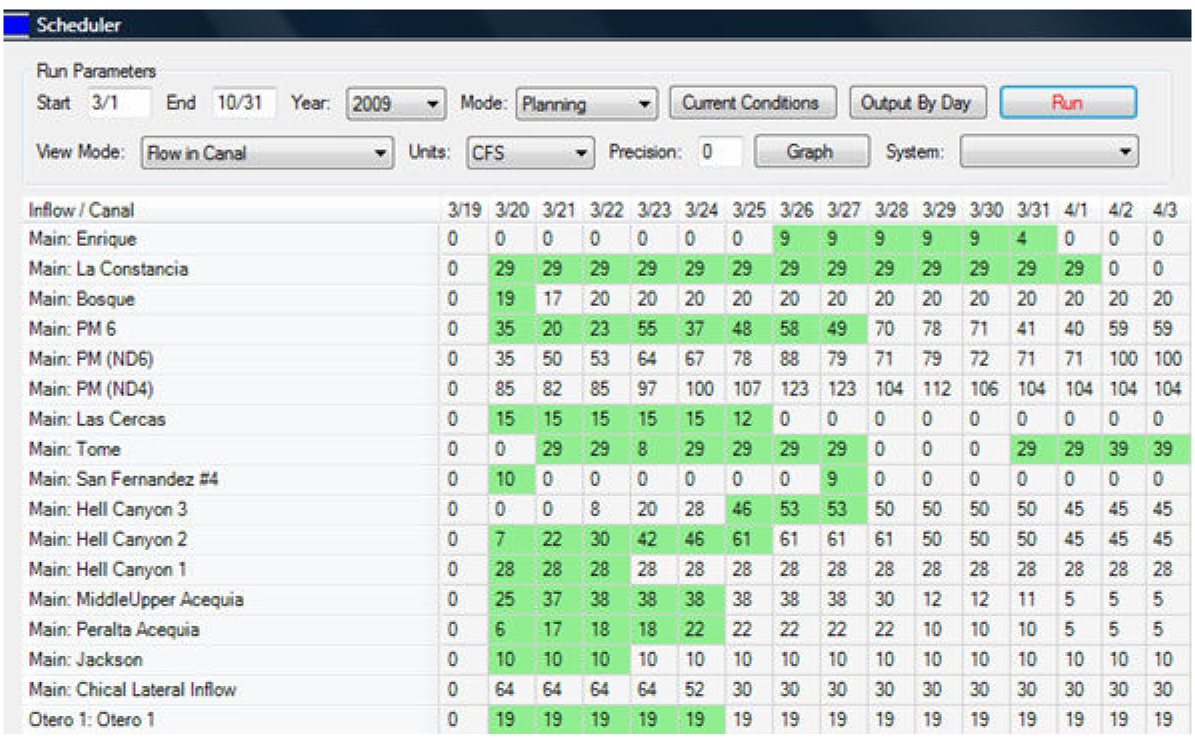


Figure 4.7: GUI for Return Flow Node

Using the information specified, the supply network module calculates a demand-based flow rate associated with each diversion to a lateral service area. The flow rate is calculated as the LDR divided by the irrigation duration. However, if the calculated flow rate exceeds the lateral capacity specified by the user, then the flow rate is set at the user-input lateral capacity. In either case, when irrigation occurs, as determined by the scheduling module, the amount of water removed from the stream link and delivered to the lateral service area for the daily time step is set equal to the volume of water that would be delivered at this flow rate over a one-day period (NMISC, 2006). This volume of water, or time-adjusted portion of LDR, is then reduced by the efficiency factor and added to the daily RAM for the service area. If the LDR is not fully delivered in the one-day irrigation, the irrigation may continue into subsequent days depending on the remaining need within the given lateral, the need of other laterals, and the assigned ranking system in the scheduler (NMISC, 2006).

4.2.3 Irrigation Scheduling Module

The irrigation scheduling module uses the information provided by the water demand and supply network modules to schedule water deliveries to meet crop demand at the lateral level. The irrigation scheduling module calculates and displays a schedule for the laterals on a given main canal. This schedule indicates how many laterals can be run at a time, how long each lateral should run, and how often (NMISC, 2006). Figure 4.8 displays an irrigation schedule created using the DSS. The module can also create monthly water delivery calendars for individual laterals. Figure 4.9 displays a calendar for an individual lateral.



Inflow / Canal	3/19	3/20	3/21	3/22	3/23	3/24	3/25	3/26	3/27	3/28	3/29	3/30	3/31	4/1	4/2	4/3
Main: Enrique	0	0	0	0	0	0	0	9	9	9	9	9	4	0	0	0
Main: La Constancia	0	29	29	29	29	29	29	29	29	29	29	29	29	29	0	0
Main: Bosque	0	19	17	20	20	20	20	20	20	20	20	20	20	20	20	20
Main: PM 6	0	35	20	23	55	37	48	58	49	70	78	71	41	40	59	59
Main: PM (ND6)	0	35	50	53	64	67	78	88	79	71	79	72	71	71	100	100
Main: PM (ND4)	0	85	82	85	97	100	107	123	123	104	112	106	104	104	104	104
Main: Las Cercas	0	15	15	15	15	15	12	0	0	0	0	0	0	0	0	0
Main: Tome	0	0	29	29	8	29	29	29	29	0	0	0	29	29	39	39
Main: San Fernandez #4	0	10	0	0	0	0	0	0	9	0	0	0	0	0	0	0
Main: Hell Canyon 3	0	0	0	8	20	28	46	53	53	50	50	50	50	45	45	45
Main: Hell Canyon 2	0	7	22	30	42	46	61	61	61	61	50	50	50	45	45	45
Main: Hell Canyon 1	0	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28
Main: MiddleUpper Acequia	0	25	37	38	38	38	38	38	38	30	12	12	11	5	5	5
Main: Peralta Acequia	0	6	17	18	18	22	22	22	22	22	10	10	10	5	5	5
Main: Jackson	0	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Main: Chical Lateral Inflow	0	64	64	64	64	52	30	30	30	30	30	30	30	30	30	30
Otero 1: Otero 1	0	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19

Figure 4.8: Irrigation Schedule Created Using the DSS

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October

Sun	Mon	Tues	Wed	Thur	Fri	Sat
				1	2	3
4	5	6	7	8	9	10 40 cfs
11 40 cfs	12 40 cfs	13 40 cfs	14 40 cfs	15	16	17
18	19	20	21	22 40 cfs	23 40 cfs	24 40 cfs
25 40 cfs	26	27	28	29	30	31

Figure 4.9: DSS Water Delivery Calendar for Individual Lateral

The module is currently set to run on a daily time step. The irrigation scheduling module calculates the daily irrigation schedule using mass balance equations and a linear programming solver. The module writes out an input file for the solver, executes the solver, and reads the solver output. In the present model version, the module displays results in tabular form. Mass balance calculations used to schedule irrigation timing and duration for lateral canal service areas are based on the consideration that the farm soil root-zone is a reservoir for water storage, for which irrigation applications are inflows and CIR is an outflow (NMISC, 2006). The mass balance approach is displayed in Equation 4.3:

$$RAM_{t+1} = I_{t+1} - O_{t+1} + RAM_t \quad \textbf{(4.3)}$$

Where I is inflow, O is outflow (which includes return flow), and t is time.

A linear programming approach is used to calculate flows to the service areas by posing the problem as a minimum cost flow optimization. The model uses the projected number of days until the soil moisture storage is depleted using a reverse-ranking system to prioritize the need for irrigation among service areas (NMISC, 2006). Based on observations of the water delivery operations, it appears that water delivery can be changed from one set of laterals to another set within one day. As travel time appears to be less than the daily time step at the present scale of model application, time lag accounting was not included in the scheduling module (NMISC, 2006).

4.3 MODEL PROGRAMMING

Model programming for scheduling water supplies to lateral service areas is described in the following section. To obtain the optimum irrigation schedule a linear programming approach is utilized. Linear programming is a method for optimizing a quantity that is defined with a mathematical expression or objective function. Constraints on variables within the objective function are also specified and must be satisfied in determining the optimum solution. This process favors water delivery to laterals with more immediate water needs, and minimizes delivery to laterals that have sufficient water (Oad et al. 2009; NMISC, 2006).

For illustration purposes, the scheduling problem is described using a hypothetical network. Figure 4.10 shows a simple irrigation network with a main supply canal and a number of laterals that represent crop water demand. The problem is similar to a transportation problem, where the service areas are demand nodes and the inflows are supply nodes (NMISC, 2006). Links are created between nodes where water can be routed. In a transportation problem, the supply needs to equal the demand; in this case, however, both under-supply (excess demand) and excess supply are possible. Therefore, to ensure that the system balances, a "dummy" source node is added that computes the water shortage in the event the system is water-short. Note that in a water-rich scenario, the dummy node is not used because it calculates only water shortage (NMISC, 2006)

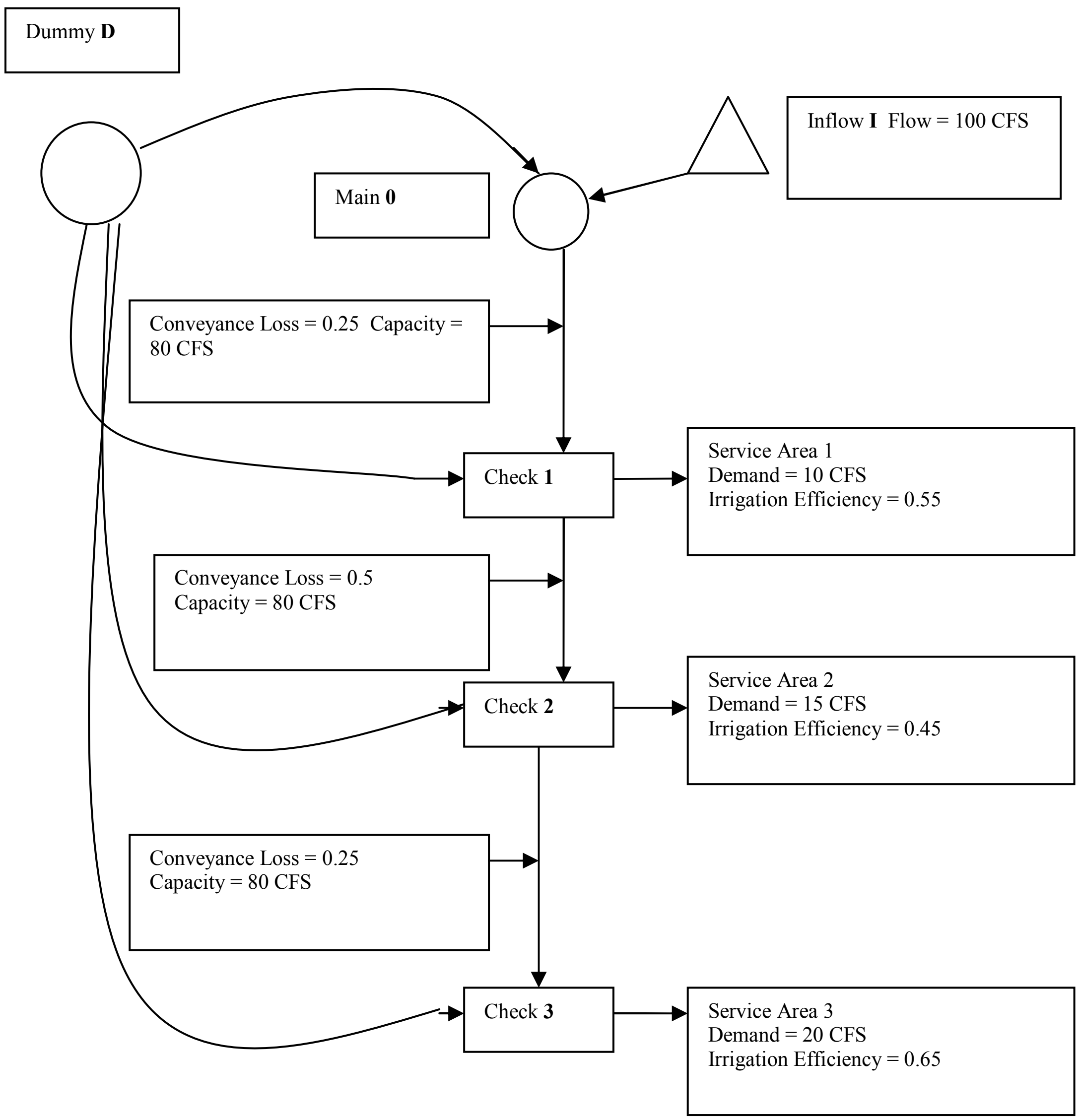


Figure 4.10: Hypothetical Irrigation Network (NMISC, 2006)

The scheduling problem is cast as a minimization problem, for which the goal is to provide water to the nodes with the greatest need for water (NMISC, 2006). This is achieved through the use of a ranking system based on water need, the use of water delivery from the dummy supply, and a set of constraints that capture mass balance conditions through the stream network. The objective function is displayed by Equation 4.4.

$$\textbf{Minimize } Z = MP_{D-0}\, X_{D-0} + MP_{D-1}\, X_{D-1} + MP_{D-2}\, X_{D-2} + MP_{D-3}\, X_{D-3} \qquad \textbf{(4.4)}$$

In this equation Z is the sum of a modified priority (MP) multiplied by the amount of supply (X) from the dummy supply to each demand node. The subscripts refer to the nodal points between which flow occurs, i.e., X_{D-1} refers to flow from the Dummy supply to Check 1, and MP_{D-1} refers to the modified priority of demand to be satisfied at Check 1 from the Dummy supply node. The MP value reflects the need-based ranking system where demand nodes with lower available soil moisture are favored for irrigation (NMISC, 2006). The objective function is solved in conjunction with a system of mass balance equations representing the actual water (and dummy water) delivered to demand nodes, along with other physically-based constraints.

The variables in the objective function represent the links in the network between the dummy supply and the demand nodes. The coefficient of each variable represents the flow "cost" of that link. In other words, delivery of water to a node without a need for water results in a higher "cost". As further discussed below, the ranking system has been assigned such that minimization of this objective function will result in minimization of water delivery to demand nodes that already have sufficient RAM (NMISC, 2006).

Constraints on the objective function solution reflect the mass balance relationships throughout the link-node network and the capacity limits on flow (NMISC, 2006). A mass-balance constraint is created for each node (including the dummy) that establishes the inflow and outflow to that node. The coefficients of the variables for each constraint (each row) are represented as a matrix, with a column for every variable in the objective function and a row for every node (NMISC, 2006). Inflows are represented as negative values and outflows as positive values. Outflow coefficients are always one, and inflow coefficients equal the conveyance loss of the connection.

The objective function is subject to the following constraints:

$$
\begin{array}{llllllllll}
\mathbf{X_{I-0}} & & & & & & & & \leq & \mathbf{I} \\
\mathbf{-X_{I-0}} & \mathbf{+ X_{0-1}} & & & \mathbf{- X_{D-0}} & & & & = & \mathbf{R_0} \\
 & \mathbf{- L_1X_{0-1}} & \mathbf{+ X_{1-2}} & & & \mathbf{- X_{D-1}} & & & = & \mathbf{R_1} \\
 & & \mathbf{- L_2X_{1-2}} & \mathbf{+ X_{2-3}} & & & \mathbf{- X_{D-2}} & & = & \mathbf{R_2} \\
 & & & \mathbf{- L_3X_{2-3}} & & & & \mathbf{- X_{D-3}} & = & \mathbf{R_3} \\
 & & & & & \mathbf{X_{D-1}} & \mathbf{+ X_{D-2}} & \mathbf{+ X_{D-3}} & < & \infty
\end{array}
$$

Where

$\mathbf{X_{0-1} \leq C_{0-1} \quad X_{1-2} \leq C_{1-2} \quad X_{2-3} \leq C_{2-3} \quad All\ X_{i-j} \geq 0}$

The variables used are:

- **I** is the total available inflow
- $\mathbf{X_{i-j}}$ is the flow in a canal reach between points i and j
- $\mathbf{C_{i-j}}$ is the maximum capacity of the canal reach between points i and j
- **D** refers to a dummy supply node that is used to force the demands and supplies to balance. The subscript 0 refers to the inflow node, and subscripts 1, 2, 3, … refer to nodal points, typically located at check structures
- $\mathbf{L_{i-j}}$ is the conveyance loss between in the canal reach between points i and j
- $\mathbf{R_i}$ is the demand (water requirement) at the nodal point indicated by the subscript (can be zero if not associated with a lateral diversion point)

For example, the third row refers to activity at check **1**. There is an inflow from the headgate ($\mathbf{- L_1X_{0-1}}$), and it is given a negative sign since by convention all inflows are negative. The conveyance loss is represented by the coefficient $\mathbf{L_1}$**.** There is an outflow to check **2** (+ $\mathbf{X_{1\text{-}2}}$) (positive sign, since by convention all outflows are positive). To ensure that the system balances, there is also an inflow from the dummy source (**-** $\mathbf{X_{D\text{-}1}}$). Because this node represents a demand, the solution for this row is constrained to be exactly the demand ($\mathbf{R_1}$). If a node represented a source, then the solution for the row would be constrained to fall between zero and the inflow. That allows the use of less than the total amount of water available if the demands are less than the supplies, or if at some point in the network the capacity is insufficient to route the inflow (NMISC, 2006). The first row in the constraint equations represents this type of node.

The conveyance loss factor specified in the supply network module is a fractional value of flow per mile. The conveyance loss (L) to be applied in the mass balance equation is calculated by subtracting the fractional value from one and raising it to the power of the number of miles of the canal segment between nodes. For example, a 3-mile reach with a 0.015 conveyance loss factor would have a loss of $[1 - (1\text{-}0.015)^3]$, or a loss of 0.0443 of the in-stream flow to this reach.

The ranking system used to derive the modified priority (MP) values for the objective function is a two-step process, involving assignment of a priority (P) based on the irrigation need at demand nodes, and then a modified priority that effectively reverses the ranking so that nodes with the least need are the preferred recipients for dummy water (NMISC, 2006). This results in the actual available water being delivered to the demand nodes with highest irrigation need. First, a priority (P) is assigned to each of the demand nodes, with smaller values indicating higher needs for irrigation. The priority is based on the number of days until the service area runs out of RAM (NMISC, 2006). If the service area is not being irrigated, 100 is added to the priority, which forces the system to favor areas being irrigated until the RAM is full again. Subsystems were added to give priority to remaining canals within a group on the assumption that if one canal service area in a subsystem is being irrigated then it is desirable that the remaining canal services areas in the same group be irrigated as well. If a service area is not being irrigated, but is in a subsystem that is being irrigated, 50, rather than 100, is added to the priority. This makes it a higher priority than service areas that are not being irrigated but are not in the subsystem. Normally a service area is irrigated only once during a schedule. However, when excess water is available, service areas in need of water are added back into the scheduling algorithm with a higher priority. The ranking system is implemented by modifying the priorities with respect to the dummy connections, effectively reversing the priorities (NMISC, 2006). Currently the modified priority (MP) for the "dummy -> node x" connection is $100{,}000/P_x$. For example, if the node has a priority of 105, then the priority assigned to the connection is 100,000/105 or 952.38. This will force dummy water to be delivered first to the lower priority nodes, leaving real water for the higher priority nodes. The modified priority (MP) values are represented by the MP variables in the objective function. The linear programming software utilized in the DSS is a package called GLPK (GNU Linear Programming Kit). The software and documentation can be downloaded from http://www.gnu.org/software/glpk/glpk.html.

4.4 DEVELOPMENT OF DSS SCHEMATICS FOR THE MRGCD

In order to create a functioning DSS model the layout of the MRGCD irrigation water conveyance system had to be represented in the DSS. This was accomplished using the GUI in the supply network module. The layout of the conveyance system was specified through a user-designed link-node network to create schematics that represented the canal layout of the MRGCD. The link-node networks in the schematics represent the canals, connections between canals or laterals, and water demand for each service area

Since the MRGCD is divided into four divisions, it was decided to represent each division using separate schematics. For the Belen Division two separate schematics were developed, because the Belen Division has large main canals on the east and west sides of the Rio Grande. The DSS schematics for the MRGCD were developed from 2005 through 2009. In 2005 the schematics for the Belen Division were developed followed by the schematic for the Socorro Division in 2006. In 2007 and 2008 the schematic for the Albuquerque Division was developed. The schematic for the Cochiti Division was completed during 2009. Currently, the entire MRGCD system is represented in the DSS and water delivery schedules can be created for every main canal, lateral, or acequia canal.

Development of the schematics required significant field reconnaissance to represent the conveyance network. The development of the schematics also required completing datasets for each division that included lateral service areas, cropping patterns and crop water requirement, soil water holding capacity, canal conveyance capacity, and river water diversions. The following sections describe the field reconnaissance and data collection required to develop a functioning DSS schematic for each division in the MRGCD.

4.4.1 Field Reconnaissance and Building Schematics

The development of the schematics required extensive field reconnaissance and analysis. The field reconnaissance to develop the DSS schematics for each division began with ditch-rider interviews and field assessments, which were conducted with each of the ditch-riders in the division. Overall, this resulted in interviews with all 31 ditch-riders in the MRGCD. The field assessment consisted of driving along all of the canals in each ditch-rider service area. During the ditch-rider interviews, hand drawn maps of the canal system in each ditch-rider area were completed. In addition to hand drawn maps, water delivery data were also obtained. Operational data obtained from interviews included the irrigation duration, the average flow required for irrigation and the time between irrigation events for each lateral service area. Other standard operational practices including the degree to which scheduled water delivery was practiced was also documented. The capacity of the canals in each ditch-rider area was also determined during the interviews.

In order to verify the hand drawn maps from the ditch-rider interviews, the MRGCD line drawings, maps, and aerial photographs were analyzed. The first step in this analysis consisted of examining the canal network in each ditch-rider service area using line drawings, maps and aerial photographs. Once this analysis was complete and the hand drawn maps from the reconnaissance were verified for each ditch-rider service area the hand drawn maps were combined to represent the entire division. One final check for the hand drawn division maps consisted of checking the entire map against the MRGCD aerial photography. The main purpose of this was to verify that the junction points in the network were correct and that no canals were left out of the maps.

Once the field reconnaissance was completed, schematics for each division were developed using the GUI in the Water Supply Module. The link and node features were used to create a network that accurately portrayed the maps created during the field reconnaissance. Main canals, laterals, and acequias were displayed using the blue canal nodes and agricultural crops were displayed using the green demand node. Drains were represented using the drain nodes. Canal connections were represented using black arrows, and drain connections were represented using pink dotted lines. During the development of the schematics, the distance of each canal was determined using GIS and aerial photographs so that canal seepage could be calculated. Once an initial schematic was completed, a series of checks were performed with the MRGCD water operations manager to ensure that the schematic represented the water delivery system correctly. To provide an example of a schematic Figure 4.11 presents the schematic developed for the Cochiti Division.

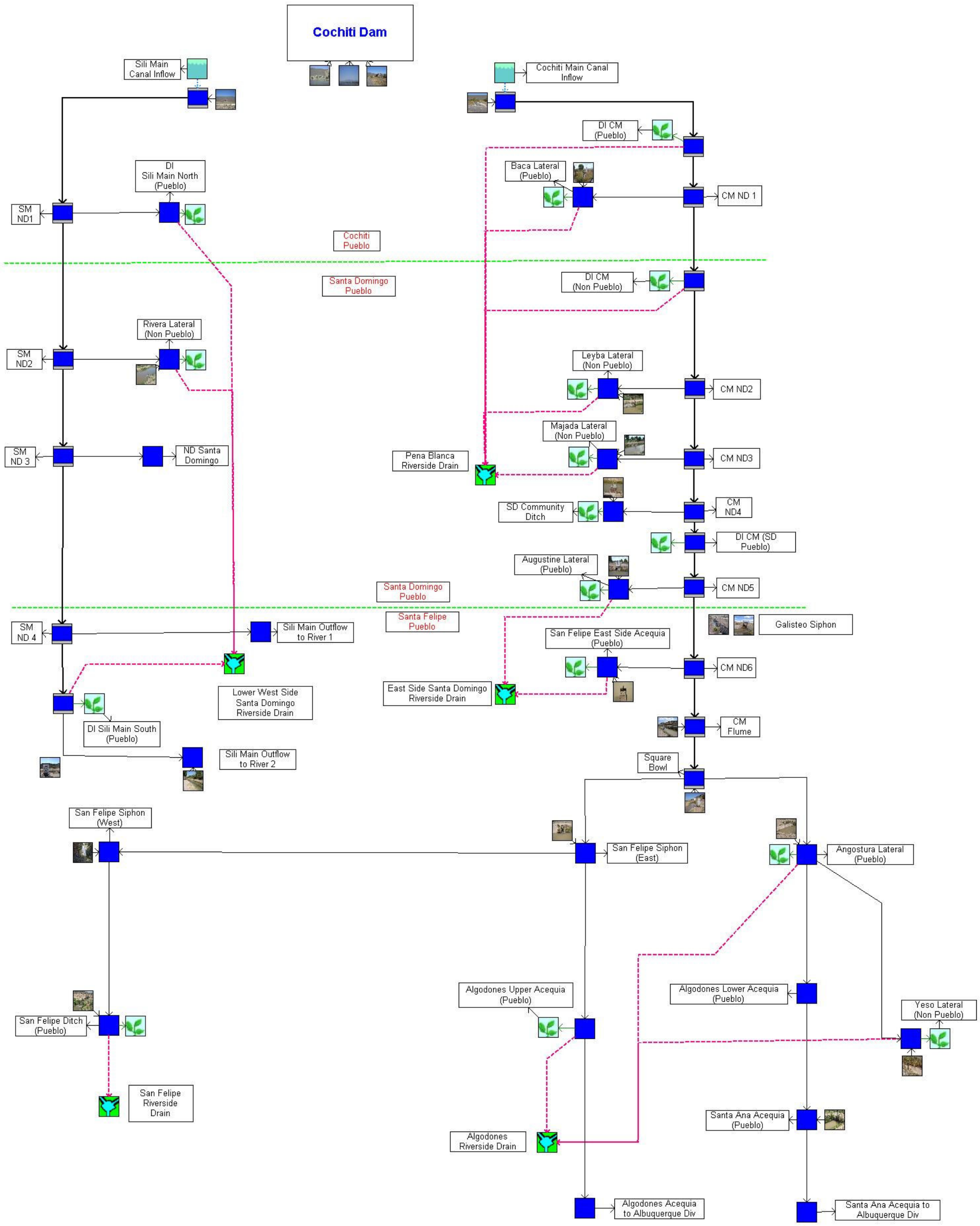


Figure 4.11: Cochiti Division Schematic

4.4.2 Development of Data Files

In order to develop a functioning DSS model for each division, the necessary data needed to be collected and incorporated into the DSS. The completed DSS data sets consist of lateral service areas, cropping patterns and crop water requirements, soil water holding capacity, canal conveyance capacity and river water diversions for the entire MRGCD.

4.4.2.1 Lateral Service Areas

The lateral service areas for each division were determined from GIS files that were obtained from MRGCD. The GIS files include the location of all main and lateral canals, the delineation of the service area for each lateral, the boundaries of each ditch-rider service area, location of gages, roads, rail lines, the Rio Grande, and the divisional boundary. The lateral service area data from the GIS shape-files were used to link each lateral to the appropriate ET Toolbox weather data and to calculate the available water holding capacity (AWC) by intersecting the shape-file with NRCS soil maps. The analysis to link weather data and determine AWC is explained in the following two sections.

4.4.2.2 Cropping Patterns and Crop Water Requirements

Determining the irrigated acreage for each division began with the processing of ditch-rider logbooks. The processing of ditch-rider logbooks consisted of manually incorporating data from the logbooks into a Microsoft Access database on a yearly basis. The current Access database contains the acreage data for the years 2003-2009. The data updated using the logbooks consisted of acreage and crop type for each parcel in the MRGCD, which the ditch-riders are required to record on a yearly basis. The current dataset contains acreage and crop type data for the entire MRGCD for the years of 2003 thru 2008. The developed database can be aggregated on a lateral service area level and easily incorporated into the DSS. Using the database, the acreage and crop type for each lateral service area in each division were determined for the 2003 through 2009 irrigation seasons. These data were incorporated into the divisional schematics using the crop area tab in the demand calculator for each demand area. Table 4.2 displays the irrigated acreage for 10 of the 161 lateral service areas in the MRGCD. A complete table can be found in Appendix C.

Table 4.2: Irrigated Acreage by Lateral Service Area for 10 of the 161 Laterals in the MRGCD

Div	Service Area	2009	2008	2007	2006	2005	2004	2003
Alb	Alameda Lateral	121	127	173	132	117	116	115
Alb	Alameda Wasteway	8	7	8	3	2	2	2
Alb	Albuquerque Main Canal	156	179	68	86	87	87	89
Alb	Allison Lateral	11	11	12	3	3	3	3
Alb	Algodones Acequia	84	82	110	91	91	91	91
Alb	Archibeque Lateral	16	16	14	7	9	9	10
Alb	Aragon Lateral	4	4	2	1	1	1	1
Alb	Arenal Acequia	58	58	43	53	57	58	57
Alb	Arenal Main Canal	807	837	804	784	840	844	839
Alb	Arenal-Atrisco Feeder	3	3	3	4	3	3	4

Weather data for each division were obtained from the Bureau of Reclamation ET Toolbox. The ET Toolbox provides daily weather data along the Rio Grande. The weather data obtained through the ET Toolbox consist of variables necessary to calculate the crop evapo-transpiration using the modified Penman-Montieth equation. The weather data from the ET Toolbox was linked to the appropriate demand area in each schematic by using the demand calculator to specify the exact location of each lateral service area with respect to the ET Toolbox grid cells.

Rainfall data were obtained separately from the National Weather Service's Hydrologic Rainfall Analysis Project (HRAP) and from Quantitative Precipitation Estimate (QPE). The HRAP divides land area into four kilometer grid cells that are used to calculate rainfall before 2006. QPE divides land area into 1 kilometer grid cells and is used to calculate rainfall from 2006 onwards. Each lateral service area in each division was overlaid with the spatially appropriate HRAP grid allowing for the calculation of rainfall on a lateral service area level. The data from the ET Toolbox website were downloaded into the DSS to complete the weather data sets for each schematic for the years 2003-2008.

4.4.2.3 Soil Water Holding Capacity

Soil property data were used to develop spatially- and depth-averaged values of available water-holding capacity (AWC) for soils in individual lateral service areas in each division. AWC forms the basis for the calculation of water demand for laterals in each schematic, as the AWC represents storage for applied irrigation water. The utilization of this water by crops will impact the timing and duration of subsequent irrigations. This section describes how the spatially- and depth-averaged values for AWC for lateral service areas were determined from available soil data. Digitally formatted GIS files of the Sandoval, Bernalillo, Valencia, and Socorro County soils were obtained from the National Resource Conservation Service (NRCS, 2004). The GIS files contain the following information:

- Soil type maps,
- Soil descriptions, and
- Available water-holding capacities (AWC) for individual soil types.

The DSS GUI interface has a soil properties calculator that allows users to determine the average water holding capacity in one foot soil increments for each demand service area. The soil properties calculator was used to determine AWC. The first step in determining AWC was to obtain a service area GIS polygon layer of each division from the MRGCD. The second step was to obtain the soil properties layer for each county from the NRCS. Once these two files were obtained the AWC was calculated by intersecting the service area GIS layer with the soil properties layer to get the weighted average of each type of soil in the service area.

The NRCS soil database contains multiple tables. The tables used for calculating AWC are the c-horizon and the component tables. The component table contains the map unit key (mukey), which is used to lookup the component key (cokey). The cokey is used in the c-horizon table to identify the AWC for a particular soil. There are three fields in the c-horizon table, *AWC_L*, the low value, *AWC_H*, the high value, and *AWC_R*, the representative value. The DSS soil properties calculator uses the representative value. Each AWC value is for a certain soil horizon between the top depth (*hzdept_r*) and the bottom depth (*hzdepb_r*). The DSS computes and stores the AWC for every inch of soil, which is then aggregated into an AWC for each foot of soil horizon up to six feet. The model then computes the weighted average AWC and the readily available moisture (RAM). The AWC for each lateral service area in each division was calculated using the soil properties calculator.

4.4.2.4 Canal Conveyance Capacity

The canal conveyance capacity data are critical to the functioning of the DSS. During the development of the schematics for each division, canal capacity data and estimates for main canals and laterals were obtained from a number of sources, including:

- MRGCD "Plan and Profile" engineering design sheets containing maximum design discharge capacities for main and lateral canals,
- GIS files,
- Estimates by ditch-riders,
- Estimates by the division manager,
- Estimates by the MRGCD Water Operations Manager.

These data were compiled into a summary table, similar to the stream summary table in the SWAP model that contains the compiled flow capacity data and estimates for each irrigation canal. The canal capacities entered into the final schematic for each division in the stream summary table were selected or interpolated from the values in this table based on knowledge of the system and field experience gained during the project field data collection efforts in 2005 thru 2009. A final check and adjustment of the conveyance capacities in the schematics for each division was performed based on the judgments of the MRGCD Water Operations Manager. Table 4.3 displays the stream summary table for 10 laterals in the MRGCD, including canal connection, canal length, conveyance loss percentage, and maximum flow capacity. All of the canal connections for the entire MRGCD are included as Appendix D.

Table 4.3: Stream Summary Table for 10 Laterals in MRGCD

Division	Canal Connection	Canal length (miles)	Loss per mile (%)	Maximum Capacity (CFS)
Albuquerque	Albuquerque Main at (650 Feeder) -> Alameda Lateral	8.15	2.73	40
Albuquerque	Albuquerque Main at (650 Feeder) -> AM 6	0.7	0.65	220
Albuquerque	Lane Lateral -> Pueblo Acequia	2.1	2.96	30
Albuquerque	Sandia Acequia -> Sandia Acequia Pueblo Demand Node	1	2.73	40
Albuquerque	Sandia Acequia -> AM 6	3.12	2.84	35
Albuquerque	Chamisal Lateral -> Pueblo Acequia	2	2.96	30
Albuquerque	Griegos Lateral -> Gallegos Lateral	3.2	1.98	80
Albuquerque	Gallegos Lateral -> Hackman Lateral	0.9	3.08	25
Albuquerque	Gallegos Lateral -> Duranes Lateral	1.25	2.07	22
Albuquerque	Gallegos Lateral -> Griegos Acequia	1.39	2.96	30

4.4.2.5 Water Diversion and Return Flow Data

Flow data for diversions and return flows, as well as key mid-division locations, are collected by the MRGCD's telemetry network. These data were made available during the season on a provisional basis via the USBR's ET-Toolbox website. At the end of the season, this data is reviewed for errors, outliers, gaps, and changing gauging station conditions. After the data were reviewed, it was provided by the MRGCD in final form for use in the DSS. The use of actual flow data allows the DSS to be run using operational mode.

CHAPTER 5 VALIDATION OF MRGCD DECISION SUPPORT SYSTEM

This chapter describes a field study that was carried out to validate key assumptions in the DSS model. This study was conducted on eight fields in the MRGCD and provided significant insight into irrigation practices in the MRG Valley. This chapter also presents analyses that were completed to examine the model formulation and programming logic of the DSS. From the monitored fields actual crop depletions were recorded and these were compared to the DSS modeled depletions to examine model accuracy. Through the validation effort the hypothesis that real time modeling using a DSS is capable of predicting crop water demand and creating water delivery schedules to meet those demands was tested.

5.1 FIELD EXPERIMENTATION TO VALIDATE MODEL ASSUMPTIONS

In order to develop the DSS it was necessary to make several assumptions of input parameters. These assumptions include on-farm application efficiency, soil moisture depletion patterns, readily available moisture remaining before irrigation occurs, and the rates of canal conveyance loss. These assumptions were made because no studies had been completed in the MRGCD to verify the values used in the DSS and values had been determined using a preliminary sensitivity analysis. During the 2008 and 2009 irrigation seasons, eight fields in the MRGCD were instrumented to determine the water use input parameters and a canal conveyance loss study was also carried out. The following sections describe the field experimentation to validate the assumptions used in the DSS.

5.1.1 Key Assumptions in the DSS Model

Several DSS model assumptions and parameters related to the irrigation system had not been determined through field measurements. Initial assumptions necessary for the development of the DSS were determined through a sensitivity analysis which is included as Appendix E. The critical assumptions about input parameters determined during the sensitivity analysis include:

- On-farm irrigation application efficiency,
- Soil moisture depletion patterns,
- Percent of RAM (readily available moisture) remaining that triggers an irrigation event, and
- Canal conveyance loss.

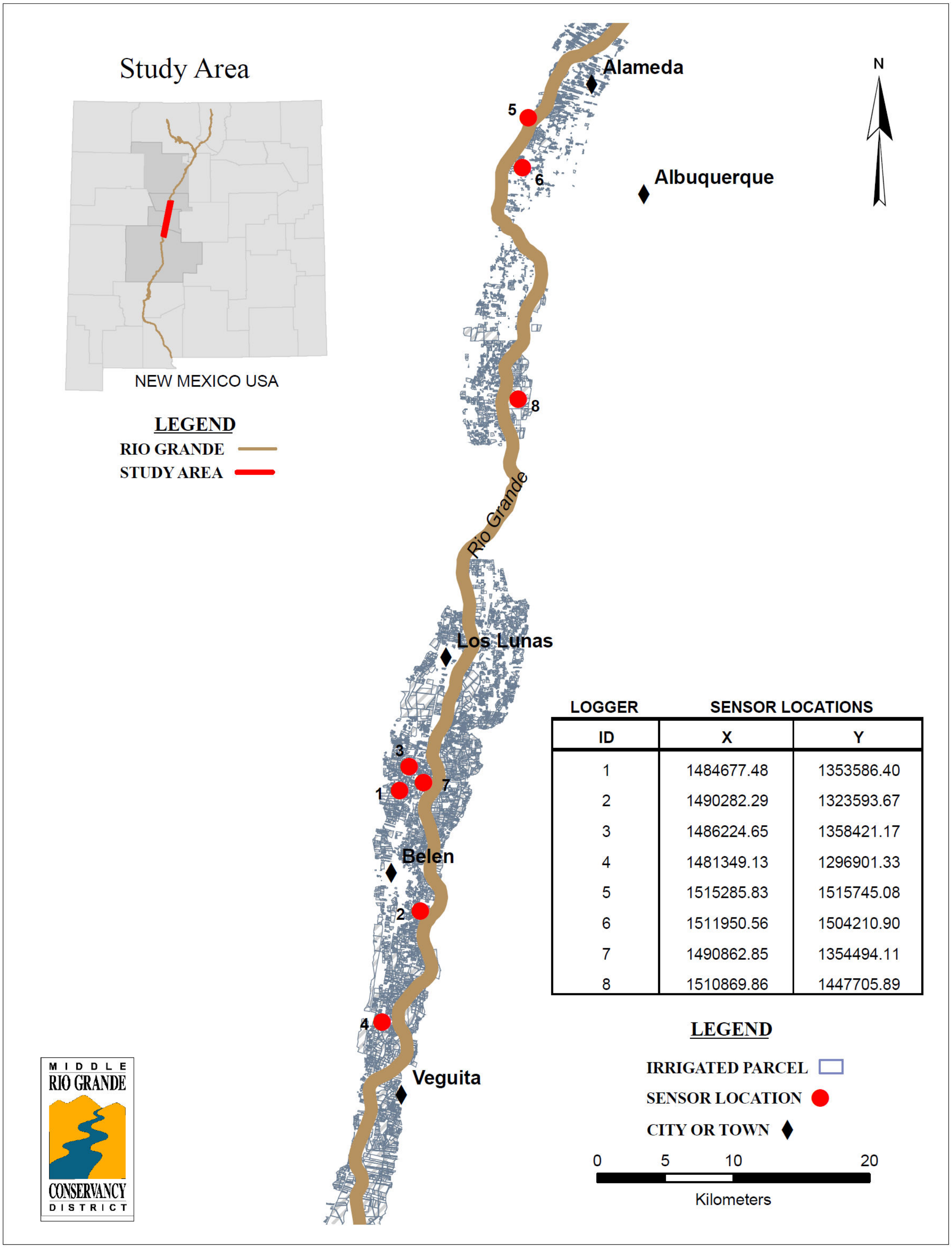
These parameters can be estimated and provided by the model users based on their experience. However, actual field measurement of these variables was considered very desirable as it can provide a guide to the future model users. Irrigation application efficiency in the MRGCD is assumed to be between 50 and 65% (Gensler, 2005). A review of studies conducted in the region suggests on-farm irrigation efficiencies of 48-50% (Wilson et al, 2003), 53-76% (URS, 2005a), and 27-52% (Lundahl, 2006). Based on the sensitivity analysis, a value of 50% was deemed to be representative. Soil moisture depletion patterns are another assumption in the DSS. The amount of soil moisture remaining that triggers irrigation is an additional factor in the DSS that has not been examined through field study. Currently the DSS is run under the assumption that farmers use the entire Readily Available Moisture (RAM) before irrigation is called for. This value was also determined during the sensitivity analysis. Canal conveyance loss throughout the MRGCD distribution network is another variable that has not been determined through field measurements. Previous measurements during the summer of 2004 suggest that some canals lose up to 4% of stream flow per mile while some sections of canal actually gain water from drainage return flow. Previously, the DSS utilized a global value of 1.5% loss per mile for all irrigation canals, which was also determined in the preliminary sensitivity analysis. In order to run the DSS with accuracy and confidence, it was considered necessary to validate the four mentioned assumptions through field experimentation.

5.1.2 Instrumentation

In order to obtain data necessary to validate the assumptions of on-farm application efficiency, soil moisture depletion patterns, and RAM remaining at the start of an irrigation event, field instrumentation was necessary. To measure the DSS input parameters in the MRGCD service area, eight representative farms were chosen in Bernalillo and Valencia Counties. Farmers were asked to volunteer for this study through the MRGCD website, the local newspapers, and their ditch-riders. The fields were chosen based on the following criteria: that they had a well distinguished permanent head ditch, where the amount of water applied could be measured, and that the field was a basin with no irrigation water leaving the downstream end of the field as surface runoff.

The reason for selecting basins was that the measurement of surface runoff from furrows and borders is difficult and often associated with high error rates. Additionally, the MRGCD irrigation policy states that there should be no surface runoff from fields, and therefore, a majority of the fields in the valley are irrigated basins. Of the eight selected fields, four were planted in alfalfa and four were planted in grass hay. These two crops represent over 85% of the irrigated acreage in the MRGCD.

The selected fields were located across a 50 mile section of the Middle Rio Grande Conservancy District in the Albuquerque and Belen Divisions. Three fields were located in the Albuquerque Division, specifically in Corrales near Alameda, Candelaria Farms, and Prices Dairy in the South Valley. Five fields were located in the Belen Division, specifically in Bosque near Veguita, on the south side of Belen near Highway 6, and three fields were located in Los Lunas/Los Chavez area. The fields were also selected to be on separate laterals in order to validate DSS model assumptions across eight separate service areas. Figure 5.1 displays the locations of the fields within the MRGCD, and Table 5.1 displays the data logger ID, GPS coordinates, lateral, and measured acreage associated with each field.



LOGGER	SENSOR LOCATIONS	
ID	X	Y
1	1484677.48	1353586.40
2	1490282.29	1323593.67
3	1486224.65	1358421.17
4	1481349.13	1296901.33
5	1515285.83	1515745.08
6	1511950.56	1504210.90
7	1490862.85	1354494.11
8	1510869.86	1447705.89

Figure 5.1: Location of Study Fields in the MRGCD

Table 5.1: Instrumented Farm Fields with Data Logger ID, GPS Coordinates, Associated Lateral, and Acreage

Logger ID	X	Y	Lateral	Acreage
1	1484677.48	1353586.40	New Belen Acequia	9.85
2	1490282.29	1323593.67	Old Jarales Acequia	12.61
3	1486224.65	1358421.17	Gabaldon Acequia	10.78
4	1481349.13	1296901.33	Sabinal 1 Acequia	4.4
5	1515285.83	1515745.08	Summerford lateral	3.655
6	1511950.56	1504210.90	Duranes Acequia	8.97
7	1490862.85	1354494.11	Los Chavez Acequia	4.49
8	1510869.86	1447705.89	Williams lateral	8.08

Each of the eight fields was instrumented with broad crested weirs and Hobo pressure transducers to determine flow applied during irrigation events. Additionally, each field was instrumented with ECH2O EC-20 capacitance based soil moisture sensors to monitor crop depletions. The details of the field instrumentation are provided in Appendix F and maps of each instrumented field are provided in Appendix G. To ensure that the soil moisture measurements were as accurate as possible a calibration was performed for each sensor installation. This calibration is explained in a journal article which is included as Appendix H. Through the instrumentation of the farm fields it was possible to create a daily water balance for each field and determine on-farm application efficiency, RAM remaining, and quantify farmer practices.

5.1.3 On Farm Application Efficiency

Since the inception of the DSS, a global value of 50% for the on-farm water application efficiency has been used. From the instrumented fields it was possible to refine this value in the DSS. For the purpose of this analysis the on farm application efficiency was defined as the water replenished for crop use divided by the total water applied. This definition of application efficiency focuses only on water for crop growth and does not include any water used for leaching salts out of the root zone. The reason that application efficiency was defined in this manner is that the DSS calculates irrigation schedules based on replenishing the soil moisture for crop growth and does not include any leaching requirements.

In order to determine application efficiency the broad crested weirs and pressure transducers installed on the eight farm fields were used to determine the total water delivered for each irrigation event during the 2008 and 2009 irrigation seasons. The method used to determine the flow rate and to calculate the total water applied for each irrigation event in cubic feet is described in Appendix F.

Once the total water applied for an irrigation event was calculated, it was possible to calculate the depth of water applied per unit area by dividing the total volume applied by the acreage of the basin that was irrigated. This resulted in a depth of water in inches applied over the monitored field. Additionally, irrigation event number, the date, duration, and average flow rate for each irrigation event were recorded. Table 5.2 displays the logger ID, irrigation event, irrigation date, total water applied, and inches applied for ten irrigation events. A table of all of the data on depth applied can be found in Appendix I.

Table 5.2: Logger ID, Irrigation Event, Date, Total Water Applied and Depth Applied for 10 Irrigation Events

Logger ID	Irrigation Event	Date	Total Water Applied (ft^3)	Depth Applied (inches)
1	1	4/14/2008	157190	6.95
1	2	5/5/2008	266004	7.44
1	3	6/1/2008	325216	9.09
1	4	6/24/2008	149748	4.19
1	5	8/6/2008	150338	4.2
1	6	9/12/2008	125121	3.5
1	1	4/13/2009	112475	3.15
1	2	5/11/2009	148812	4.16
1	3	6/18/2009	173791	4.86
1	4	7/20/2009	113443	3.17

The next step in calculating the application efficiency was determining the water available for crop use that was replenished during each irrigation event. This was possible using the data collected from the installed EC-20 soil moisture sensors. The soil moisture sensor data, corrected using the developed laboratory calibration equations for each specific sensor installation, provided the volumetric soil moisture content before the irrigation event and after field capacity was reached. The difference between the volumetric water content before the irrigation event and field capacity represented the amount of water stored in the root zone for beneficial crop use. This data was recorded at both the 8 inch and 24 inch sensor location for each field for each irrigation event. To calculate the water stored in the soil for beneficial crop use in inches the 8 inch sensor was deemed to be representative of the first 16 inches of root depth for both the alfalfa and grass hay fields. The 24 inch sensor was chosen to represent the subsequent 20 inches of root depth for grass hay and the subsequent 32 inches for alfalfa. For grass hay and alfalfa this represented a 36 inch and 48 inch effective total root zone, respectively. These values were chosen based on 12 years of research conducted by Garcia et al. (2008) at the Natural Resource Conservation Service (NRCS), which was conducted in the Middle Rio Grande and Mesilla Valleys to determine the root depths that were effectively able to utilize and deplete soil moisture.

Once the effective root depth was determined, the root depth associated with each sensor and crop type was multiplied by the difference between the volumetric water content at field capacity and volumetric water content before the irrigation event took place for the 8 inch and 24 inch sensor. This yielded the water available for crop use in inches for the upper 16 inches and either lower 20 inches for grass hay or 32 inches for alfalfa. These two values were added together to give the total water in inches available for crop use applied during the irrigation event. The total water available for crop use was then divided by the total water applied to determine application efficiency. The application efficiency for all 144 irrigation events was calculated from the collected data. Table 5.3 displays the results of the application efficiency analysis for 10 irrigation events. The results from all 144 irrigation events are presented in Appendix J.

Table 5.3: Irrigation Event, Date, Depth Applied, Moisture Applied for Beneficial Crop Use and Application Efficiency for 10 Irrigation Events

Logger ID	Irrigation Event	Date	Depth Applied (inches)	Moisture Applied for Crop Use (inches)	Application Efficiency (%)
1	1	4/14/2008	6.95	4.64	67%
1	2	5/5/2008	7.44	1.92	26%
1	3	6/1/2008	9.09	3.36	37%
1	4	6/24/2008	4.19	2.24	53%
1	5	8/6/2008	4.2	1.76	42%
1	6	9/12/2008	3.5	2.4	69%
1	1	4/13/2009	3.15	2.56	81%
1	2	5/11/2009	4.16	2.56	62%
1	3	6/18/2009	4.86	2.56	53%
1	4	7/20/2009	3.17	1.12	35%

The data presented in Appendix J displayed significant variability with a range in application efficiency from 8% to 100%. The mean value for all 144 irrigation events was found to be 44.4% with a standard deviation of 24.4%. The calculated mean value represent a slightly lower application efficiency value than the 50% assumed in the DSS. To address the variability in the collected data and determine a single value to utilize in refining the DSS, a histogram of the collected data was created. Figure 5.2 displays the histogram of application efficiency.

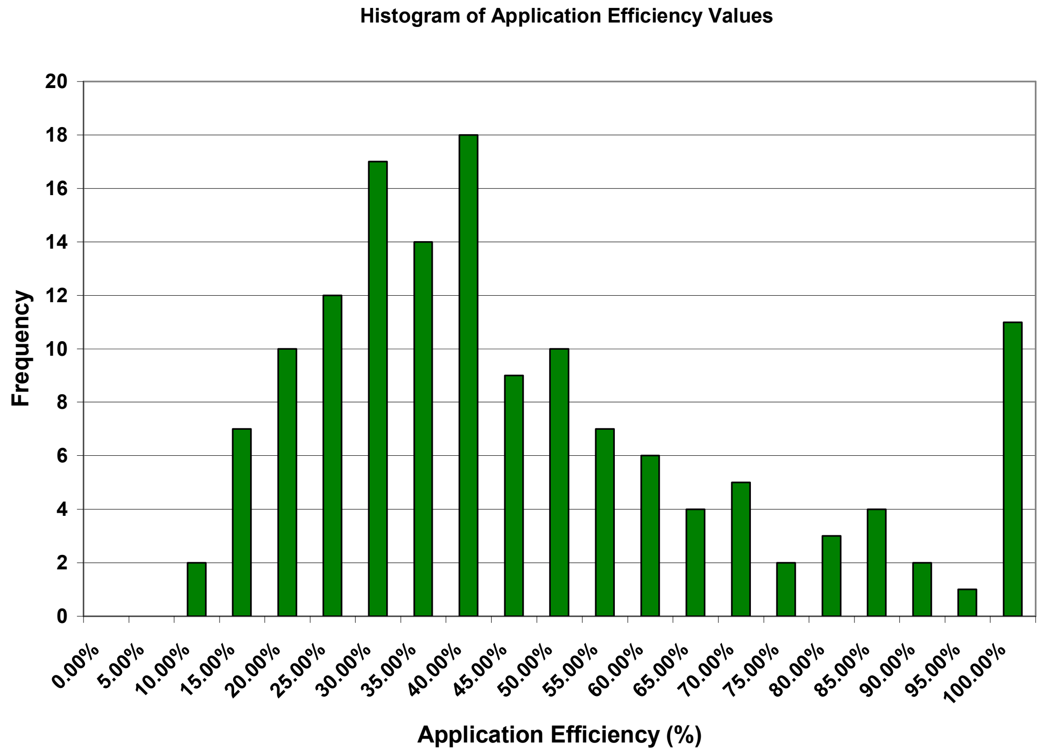


Figure 5.2: Histogram of Application Efficiency

The developed histogram displayed a nearly normal distribution about the mean value but was skewed slightly to the right due to 11 irrigation events with an application efficiency of 100%. From the developed histogram it became clear that the majority of irrigation events exhibited application efficiencies reflected by the calculated mean value. Using the developed histogram it was also possible to calculate the probability that the application efficiency would fall within one standard deviation of the calculated mean. The probability that the application efficiency of an irrigation event would fall within one standard deviation was found to be 112 out of 144 irrigation events resulting in a probability value of 0.78. This indicates that 78% of the irrigation events were within one standard deviation of the calculated mean. Based on the analysis of the histogram and probability the revised value for application efficiency of 45% will be incorporated in the DSS, which will allow for more precise representation of farmer practices. In the future the DSS could be revised to include a Monte Carlo simulation of the variability found in the application efficiency values instead of using a single number.

Several irrigation events exhibited an application efficiency of 100% and indicate possible under irrigation. Such results also point to possible measurement errors and residual moisture that is used by plants but not accounted for in calculations related to an irrigation event. One reason for possible errors could be due to the fact that only one sensor location was installed for each field due to budget constraints. Spatial variability in soil and topography that could not be measured due to a single sensor location could be the cause of uneven water distribution during the irrigation event. Differences in moisture uptake by plants due to spatial root variability could also be the cause this discrepancy.

5.1.4 RAM Remaining Before Irrigation

The assumption that has been used in the DSS for soil moisture remaining before irrigation takes place has been that the entire readily available moisture is depleted before farmers in the MRG Valley irrigate their fields. From the data collected during the 2008 and 2009 irrigation season it was possible to calculate the actual RAM remaining at the beginning of irrigation events, as well as the management allowed depletion factor (MAD) used by farmers.

The first step in determining RAM remaining when irrigation occurred was to determine the Total Available Moisture (TAM) for each instrumented field. This was accomplished by subtracting the volumetric water content at the wilting point from the volumetric water content at field capacity and multiplying this value by the root depth represented by each sensor. To calculate the TAM the eight inch sensor was deemed to be representative of the first 16 inches of root depth for both the alfalfa and grass hay fields. The 24 inch sensor was chosen to represent the subsequent 20 inches of root depth for grass hay and the subsequent 32 inches for alfalfa. For grass hay and alfalfa this represented a 36 inch and 48 inch effective root zone, respectively. These values were chosen based on research conducted by Garcia (2008) at the NRCS, which was conducted in the Middle Rio Grande Valley and Mesilla Valley to determine the root depths that were effectively able to utilize and deplete soil moisture. This calculation was carried out for the 8 inch and 24 inch sensor. The addition of these values provided the TAM for each field. The equation used to calculate the TAM for each field is displayed as Equation 5.1.

$$[(FC_{8"} - WP_{8"})*RZ_{\text{represented by 8" sensor}} + (FC_{24"} - WP_{24"})*RZ_{\text{represented by 24" sensor}}] \quad \textbf{Eq 5.1}$$

The field capacity used in Equation 5.1 was determined from the collected soil moisture sensor data, corrected using the developed laboratory calibration equations, as a sharp break in the soil moisture depletion curves was observed as gravitational drainage ceased. The field capacity values were compared to lab results of a pressure plate analysis conducted at the Colorado State University soils lab to ensure accuracy. The wilting point was determined through pressure plate analysis for each individual sensor installation. The TAM was calculated for a total of 144 irrigation events as the field capacity changed slightly during the irrigation season due to compaction from field trafficking and soil expansion from irrigation events.

The next step was to calculate the TAM utilized by crops between each irrigation event. The difference between the volumetric water content before the irrigation event and field capacity represented the amount of TAM depleted by crops between irrigation events. This value was previously calculated in the analysis of application efficiency as the water available for crop use replenished by irrigation events. Once the TAM and the TAM utilized between irrigations was calculated, it was possible to determine the MAD by dividing the TAM utilized by the TAM. From the 144 irrigation events it was determined that the mean MAD used by farmers in the MRG Valley was 0.41 for grass hay and 0.34 for alfalfa. This indicates that farmers are averse to stressing their crops and irrigate frequently before a significant amount of the available soil moisture is depleted. These values will be used to refine the MAD used under the crop characteristics tab in the DSS. Table 5.4 displays the MAD values calculated for 10 irrigation events. The calculated values for MAD for all 144 monitored irrigation events are included in Appendix K.

Table 5.4: Logger ID, Irrigation Event, Date, and MAD Calculated for 10 Irrigation Events

Logger ID	Irrigation Event	Date	MAD
1	1	4/14/2008	0.6
1	2	5/5/2008	0.24
1	3	6/1/2008	0.45
1	4	6/24/2008	0.29
1	5	8/6/2008	0.2
1	6	9/12/2008	0.29
1	1	4/13/2009	0.26
1	2	5/11/2009	0.29
1	3	6/18/2009	0.28
1	4	7/20/2009	0.13

The RAM remaining before irrigation occurred was calculated by first calculating the total RAM. This was done by multiplying the TAM previously calculated for each irrigation event by the MAD calculated for the two crop types of grass hay and alfalfa. The second step was to calculate the RAM utilized by the crop between irrigation events. This was done in the previous analysis of TAM and is the same value as the TAM utilized by the crops between irrigation events. The third step was to calculate the RAM remaining when an irrigation event occurred. This value was calculated by subtracting the RAM utilized by the crop from the RAM. The final step was to calculate the percent of RAM remaining when irrigation events occurred. This was done by dividing the RAM remaining by the total RAM. . Table 5.5 displays the percent RAM remaining calculated for 10 irrigation events. The calculated values for RAM remaining for all 144 monitored irrigation events are included in Appendix L.

Table 5.5: Logger ID, Irrigation Event, Date, and % RAM Remaining Calculated for 10 Irrigation Events

Logger ID	Irrigation Event	Date	% RAM Remaining
1	1	4/14/2008	0%
1	2	5/5/2008	26%
1	3	6/1/2008	0%
1	4	6/24/2008	13%
1	5	8/6/2008	39%
1	6	9/12/2008	13%
1	1	4/13/2009	21%
1	2	5/11/2009	12%
1	3	6/18/2009	16%
1	4	7/20/2009	61%

The mean percent of RAM remaining for when irrigation events occur was found to be 23% for the 144 irrigation events with a standard deviation of 24%. It was also observed that there were a significant amount of values representing 0% RAM remaining when irrigation occurred. To analyze the variability and distribution of the data a histogram was developed. Figure 5.3 displays the histogram of % RAM remaining for the 144 monitored irrigation events.

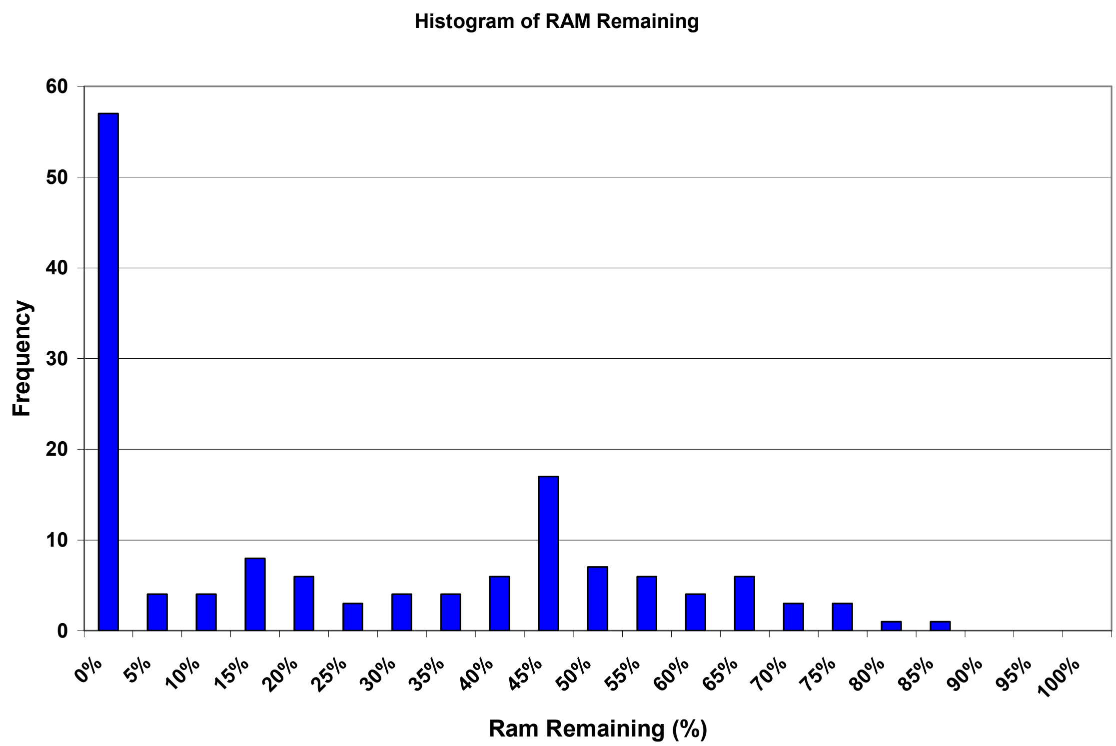


Figure 5.3: Histogram of % RAM Remaining

The developed histogram displayed a skewed distribution with a skewness coefficient of 0.54. This indicated that the tails of the distribution represented a majority of the irrigation events. This becomes quite apparent upon visual inspection of the histogram as 57 irrigation events exhibited a % RAM remaining of 0%. Using the developed histogram it was also possible to calculate the probability that the % RAM remaining would fall within one standard deviation of the mean value. The probability that the % RAM remaining when irrigation occurred would fall within one standard deviation was found to be 120 out of 144 irrigation events, resulting in a probability value of 0.83. This indicates that 83% of the % RAM remaining values were within one standard deviation of the mean. Based on analysis of the histogram and probability the revised value for % RAM remaining of about 20% will be incorporated into the DSS. This value will be incorporated in the DSS to represent the practice that farmers in the MRG irrigate when there is still a portion of the RAM remaining. In the future the DSS could be revised to include a Monte Carlo simulation of % RAM remaining to represent the variability found during the field experimentation.

The numbers for MAD and RAM remaining before irrigation occurs determined during this study are very conservative and indicate that farmers generally irrigate before the RAM is entirely depleted. Since water is not metered, farmers have no incentive to conserve water and watering before the RAM is entirely depleted ensures that crop stress and yield loss does not occur.

The percent of RAM remaining at the start of the irrigation season is another input factor that had not been determined. This value is crucial for developing the first schedules of the season in the DSS. From the collected data it was possible to calculate the percent of RAM remaining at the start of the irrigation season for the 2008 and 2009 irrigation seasons. The mean percent RAM remaining at the beginning of the irrigation season was calculated for both grass hay and alfalfa fields together. The mean percent of RAM remaining in the eight fields monitored was determined to be 7% at the start of the

2008 irrigation season and 11% at the start of the 2009 season. These values will serve as a guide for users of the DSS in inputting appropriate moisture levels at the start of the irrigation season.

5.1.5 Canal Seepage Loss

In order to determine conveyance losses in the MRGCD canals, three community farm channels (acequias), three laterals, and three main canals were selected for conveyance loss measurement. The measurements were conducted during the early, middle and late part of the irrigation season. The main canals measured were the Belen Highline Canal, the Socorro Main Canal, and the Albuquerque Main Canal. The lateral size canals measured were the New Belen Acequia, the Peralta Acequia, and the Barr Main Canal. The acequia size canals measured were the Bernalillo Acequia, the Sili Main Canal, and the Williams Lateral.

For each canal a measurement site was established where a significant length of canal (in most cases over 2 miles) was available for inflow and outflow measurements without surface abstractions of the flow. To insure that all irrigation had ceased on the canal, the measurement section was driven to check that all turnouts along the canal were indeed closed. In order to verify that storage was not changing, pressure transducers and temporary staff gages were used during inflow and outflow measurements to monitor water level fluctuations. The pressure transducers used were HOBO data loggers manufactured by Onset Incorporated. From the data collected by the Hobo pressure transducers it was possible to determine the exact fluctuation in canal water level. If the fluctuations in the water level exceeded 2.5% of the total maximum depth, the measurement was discarded and repeated. Flow measurements were completed using a Stream Pro Acoustic Doppler Current Profiler (ADCP). The methodology and data collected during the study are described in detail in a journal article included as Appendix M. Maps of all canal measurement locations are included in Appendix N.

The average canal conveyance loss for the completed 27 measurements is 2.4% per mile. The average for main canals is 1.03% per mile, the average for lateral canals is 3.11% per mile, and the average of acequias is 2.96% per mile. The seepage loss rates obtained resemble results obtained by Fipps (2001) for canal seepage in the Lower Rio Grande Valley. The suspected reasons for lower seepage rates in main canals include sedimentation, groundwater, and maintenance. The main canals in the MRGCD are all directly connected to the Rio Grande and receive significant sediment loads. As water is conveyed down the main canals the sediment eventually settles out in the main canals reducing sediment load in lateral and acequia canals. The settling out in main canals results in soil pores being clogged with finer silt and clay sediment, thereby reducing overall seepage. Another reason for reduced seepage in main canals is the close proximity to the river and subsequent groundwater. Since the main canals originate at the Rio Grande they are not elevated above the river and could be connected to groundwater. Such close proximity to the groundwater would result in a small or negligible gradient for seepage from canal bottoms and to groundwater. Finally, the main canals in the MRGCD receive the most attention when it comes to maintenance and dredging. The main canal shapes in the MRGCD most closely represent the optimized canal sections for minimized seepage presented by (Swamee et al. 2000), and the continued maintenance of these main canals results in a more efficient canal shape and optimized water conveyance.

Further analysis of the data showed that trends in canal seepage rate existed for upstream flow rate, and the three canal geometry properties of upstream wetted perimeter, upstream flow area, and upstream top width. The data showed that as canal inflow rate decreased the seepage increased. For the wetted perimeter, flow area, and top width data, the seepage increased as these values decreased. In order to develop predictive equations, the characteristics of the upstream cross section were related to the percent loss per mile.

Correlation between Seepage Loss and Flow Rate

Analyzing the data for seepage rate versus upstream flow rate exhibited an exponential trend. This relationship exhibited a correlation coefficient r^2 of 0.801 and is displayed in Figure 5.4 as well as Equation 5.2.

$$\mathbf{S = 3.7639e^{-0.008Q}} \qquad \textbf{Equation 5.2}$$

Where S= percent seepage loss per mile (%)
Q = inflow discharge (ft^3/s)

Correlation between Seepage Loss and Canal Geometry

In addition to analyzing the inflow rate versus seepage loss, geometric properties of the inflow canal were plotted against the seepage rate. The three geometric properties that exhibited the most significant predictive equations were wetted perimeter, flow area, and channel top width. The data for seepage rate versus upstream wetted perimeter exhibited an exponential trend. The exponential relationship developed exhibited a correlation coefficient r^2 of 0.792 and is displayed in Figure 5.5 as well as in Equation 5.3.

$$S = 7.3155e^{-0.0519P}$$ **Equation 5.3**

Where S = percent seepage loss per mile (%)
P = wetted perimeter (ft)

The data for seepage rate versus upstream flow area also exhibited an exponential trend. The exponential relationship developed exhibited a correlation coefficient r^2 of 0.760 and is displayed in Figure 5.6 as well as in Equation 5.4.

$$S = 4.3489e^{-0.0164A}$$ **Equation 5.4**

Where S = percent seepage loss per mile (%)
A = inflow area (ft^2)

The data for seepage rate versus upstream top width also exhibited an exponential trend. The exponential relationship developed exhibited a correlation coefficient r^2 of 0.777 and is displayed in Figure 5.7 as well as in Equation 5.5.

$$S = 6.5959e^{-0.054T}$$ **Equation 5.5**

Where S = percent seepage loss per mile (%)
T = top width (ft)

Overall, the four developed equations display similar exponential trends. The variation in the collected data is minimal, and the four equations are significant as the correlation coefficient (r^2) is not less than 0.760 for any of the developed equations. These equations present the opportunity to predict canal seepage losses based on the four easily measured parameters of inflow rate, wetted perimeter, flow area, and top width.

These equations should only be applied to similar systems and to canals that are comparable in size to the ones measured during this study.

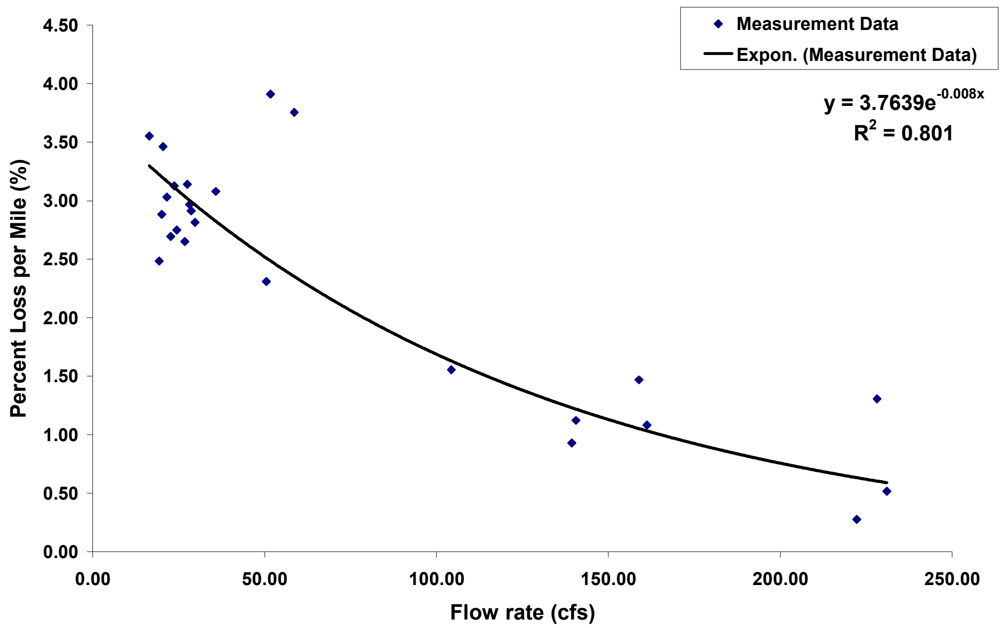


Figure 5.4: Relationship between Upstream Flow Rate and Seepage Loss

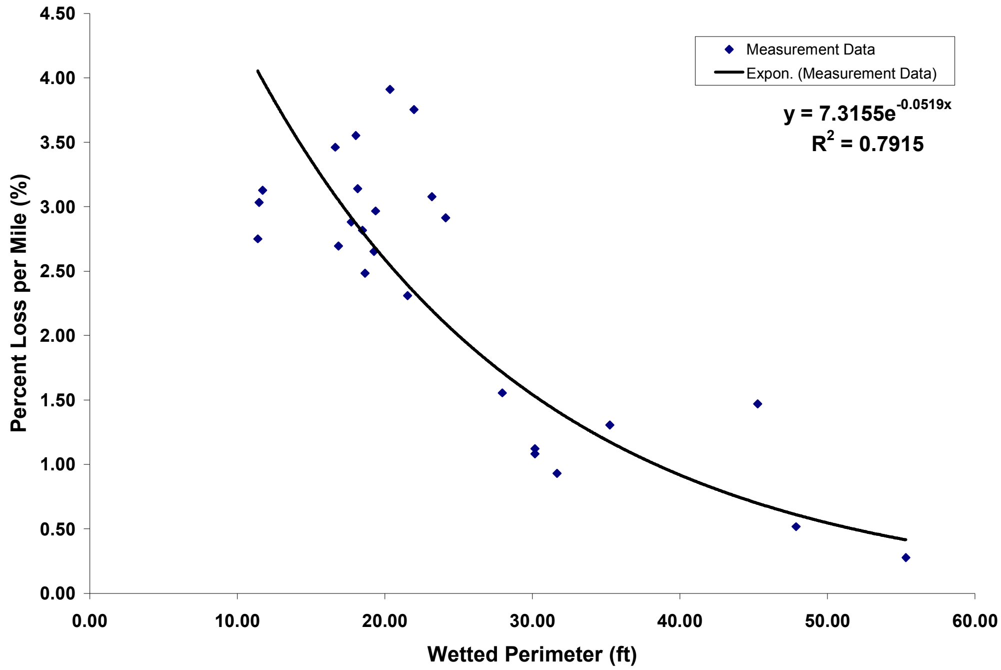


Figure 5.5: Relationship between Upstream Wetted Perimeter and Seepage Loss

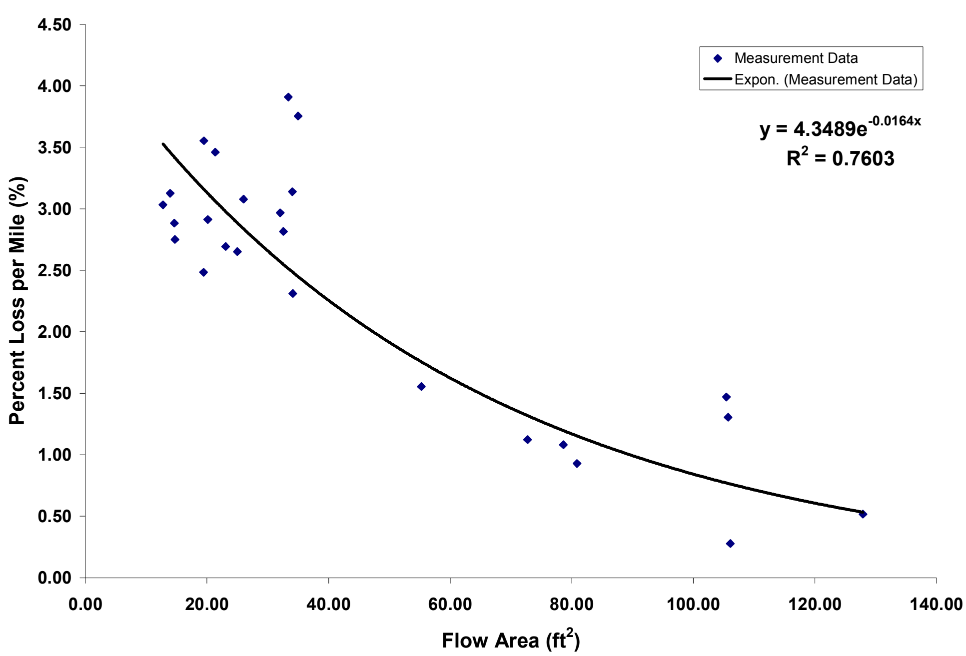


Figure 5.6: Relationship between Upstream Flow Area and Seepage Loss

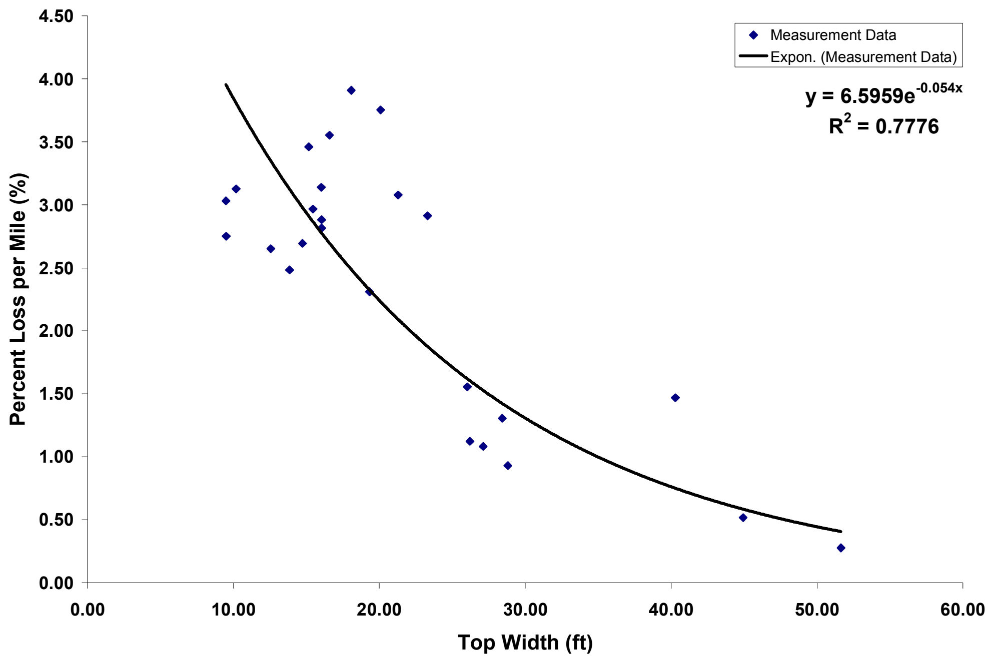


Figure 5.7: Relationship between Upstream Top Width and Seepage Loss

All of the developed equation types were determined by selecting the equation type with the highest coefficient of determination. The developed equations only apply to the Middle Rio Grande Valley or to irrigation systems that are geologically and hydrologically similar. The two most useful equations to the MRGCD will most likely be Equation 5.2 and Equation 5.5, which relate canal inflow and top width to seepage loss rate, respectively. The variables of canal inflow and canal top width are easily obtainable and require minimal effort for data collection. The MRGCD utilizes a network of automated measurement stations (Gensler et al. 2009), which will aid in determining canal inflow, that can then directly be related to a canal seepage rate. Determining the canal top width will also be quite straightforward, as many bridges exist across canals allowing ditch-riders and water masters to measure the canal top width to obtain an estimate for canal seepage.

Using diversion records obtained from the automated measurement network, the MRGCD will also be able to quantify the aquifer recharge from the canal system in the Middle Rio Grande Valley. The length of each canal as well as the inflow for said canal is well defined, and the developed equations will allow for calculation of canal seepage volume. The benefit to the MRGCD will be proving the amount of water that the canal system recharges to the regional aquifer. The city of Albuquerque and several smaller communities pump from the regional aquifer, and it is believed that aquifer levels are maintained through the seepage from the Rio Grande and MRGCD irrigation canals. Quantifying the amount of seepage that occurs from the MRGCD canals will prove the benefit that the canal network has on the local aquifer and aid the MRGCD in water rights litigation. Application of the developed equations will also have the benefit of determining areas where canal maintenance or lining would have the greatest benefit in water saving.

The predictive equations have also been used in the DSS. The equation relating canal inflow and seepage loss has been added into the canal connection summary table of the DSS. Using the standard global 1.5% loss per mile in the DSS, the total canal seepage loss for the MRGCD was calculated to be 57,886 acre feet in 2008. Using the equations developed during the seepage study in the DSS, the seepage rate increased to 70,579 acre feet in the operational mode for 2008. Table 5.6 presents the results of this comparison.

Table 5.6: Comparison of Total Seepage Losses using 1.5% per Mile and the Developed Equation for the 2008 Irrigation Season

Division	DSS in Operation Seepage at 1.5% (AF)	DSS in Operation Seepage Equation (AF)
Cochiti	8240	12746
Albuquerque	8922	18139
Belen	22326	29441
Socorro	18398	10253
Total	57886	70579

The results of the comparison show that the DSS was previously under-predicting the total seepage, which would result in less water available for irrigators than they would actually require. Through the development of the equations from the seepage study, the accuracy of the DSS has been greatly improved by representing the seepage rates for a variety of canal sizes based on field measurements.

5.2 DESCRIBING FARMER PRACTICES IN THE MRGCD

Prior to the instrumentation of the eight farm fields in the Middle Rio Grande Valley little was known about farmers water management practices and crop yields. From the data collected during the field study it was possible to describe parameters related to farmer's irrigation practices and water management as well as crop yields. The information presented in the following two sections elucidates farmer's practices and has been quite useful to the MRGCD Water Operations Manager.

5.2.1 Irrigation Practices and Water Management

Prior to the field instrumentation described in Appendix F only two studies regarding on farm water use had been conducted in the MRGCD. One study (Lundahl, 2006) focused on one alfalfa field for one irrigation season, and another study (URS, 2005a) examined water management on a field in Socorro but did not actually measure the amount of water applied to the field.

The eight instrumented fields provided the opportunity to examine irrigation duration, flow rates, total water applied, application efficiency, frequency of irrigation, RAM, and MAD values over a period of two years and 144 total irrigation events.

5.2.1.1 Irrigation Duration and Flow Rate

Irrigation duration is defined as the amount of time it takes to complete an irrigation event and is directly linked to the flow rate applied. Using the installed Hobo pressure transducers it was possible to determine the start time and end time for each of the 144 monitored irrigation events. The flow rate was also determined using the broad crested weirs installed to measure the flow for each field.

The four monitored grass hay fields exhibited a mean irrigation duration of three hours and fifty eight minutes for a mean field size of 5.15 acres during the two year study. This amounts to an average irrigation time of 46 minutes per acre. This value corresponds well with the MRGCD water policy, which suggests one hour per acre as an appropriate irrigation duration. The mean flow rate for the irrigation events on grass hay fields was found to be 7.8 cfs. Table 5.7 presents the irrigation duration and flow rate values for the grass hay fields.

Table 5.7: Irrigation Duration and Flow Rate Values on Monitored Grass Hay Fields in 2008 and 2009

Logger ID	Irrigation Event	Date	Irrigation Duration (hr:min)	Flow Rate (cfs)
4	1	4/19/2008	3:10	6.40
4	2	5/5/2008	3:00	5.07
4	3	5/23/2008	3:00	6.22
4	4	6/7/2008	5:00	5.08
4	5	6/27/2008	4:20	4.77
4	6	7/9/2008	4:00	5.12
4	7	8/6/2008	5:00	5.84
4	8	8/20/2008	3:10	6.72
4	9	9/10/2008	5:30	3.53
4	10	9/23/2008	2:50	6.04
4	11	10/30/2008	4:50	5.05
4	1	3/10/2009	4:40	5.87
4	2	4/11/2009	3:20	7.33
4	3	4/22/2009	4:10	3.94
4	4	5/9/2009	3:30	6.86
4	5	5/26/2009	4:40	4.89
4	6	6/9/2009	3:40	5.82
4	7	7/6/2009	4:00	5.46
4	8	7/22/2009	3:40	6.35
4	9	8/10/2009	4:50	1.92
4	10	9/2/2009	5:20	5.09
4	11	9/17/2009	4:10	4.88
5	1	4/17/2008	3:15	6.52
5	2	5/1/2008	2:30	7.10

Logger ID	Irrigation Event	Date	Irrigation Duration (hr:min)	Flow Rate (cfs)
5	3	5/15/2008	2:45	6.62
5	4	5/29/2008	2:55	4.06
5	5	6/12/2008	4:15	3.63
5	6	6/26/2008	4:00	4.21
5	7	7/10/2008	4:05	4.45
5	8	7/25/2008	5:20	4.75
5	9	8/7/2008	3:35	4.26
5	10	8/21/2008	5:15	3.89
5	11	9/4/2008	5:00	5.32
5	12	9/18/2008	4:00	5.64
5	13	10/2/2008	3:15	5.36
5	14	10/23/2008	3:45	3.55
5	1	3/26/2009	2:30	4.05
5	2	4/16/2009	1:30	2.93
5	3	5/7/2009	6:45	1.53
5	4	5/23/2009	6:00	2.67
5	5	6/5/2009	3:00	4.62
5	6	6/18/2009	5:00	4.19
5	7	7/2/2009	5:00	2.96
5	8	7/16/2009	5:50	4.68
5	9	7/30/2009	4:15	5.59
5	10	8/13/2009	5:00	5.79
5	11	9/3/2009	5:30	5.31
5	12	9/24/2009	4:00	4.06
5	13	10/16/2009	4:50	4.35
5	14	10/29/2009	2:40	3.90
7	1	4/25/2008	1:30	7.55
7	2	5/9/2008	3:00	9.03
7	3	6/1/2008	2:30	7.39
7	4	6/23/2008	5:30	7.09
7	5	7/13/2008	4:30	5.44
7	6	8/8/2008	4:00	8.16
7	7	9/5/2008	4:40	5.82
7	8	9/21/2008	3:50	5.20
7	1	4/10/2009	4:00	5.73
7	2	4/27/2009	2:40	7.21
7	3	5/15/2009	2:50	8.77
7	4	6/9/2009	3:45	7.03
7	5	7/17/2009	5:00	6.91
7	6	8/21/2009	5:30	7.80
7	7	9/3/2009	4:00	8.28
7	8	10/4/2009	4:00	3.30
8	2	5/24/2008	3:00	22.89
8	3	6/6/2008	4:00	21.73
8	4	7/1/2008	3:00	17.28
8	5	7/19/2008	3:00	16.90

Logger ID	Irrigation Event	Date	Irrigation Duration (hr:min)	Flow Rate (cfs)
8	6	8/3/2008	3:00	15.93
8	7	8/28/2008	3:00	17.58
8	8	9/19/2008	3:00	20.14
8	1	3/16/2009	3:00	12.95
8	2	4/2/2009	4:00	15.73
8	3	4/25/2009	4:00	19.38
8	4	6/2/2009	4:30	17.07
8	5	6/21/2009	4:30	12.47
8	6	7/4/2009	4:00	15.20
8	7	7/24/2009	4:00	14.90
8	8	8/13/2009	4:00	15.39
8	9	9/10/2009	5:00	19.74
8	10	10/6/2009	4:00	16.79

The irrigation duration values for the grass hay fields were examined to determine if any temporal trends were evident. It was found that no significant trend existed during either the 2008 or 2009 irrigation seasons. Figure 5.8 presents the irrigation duration values over time

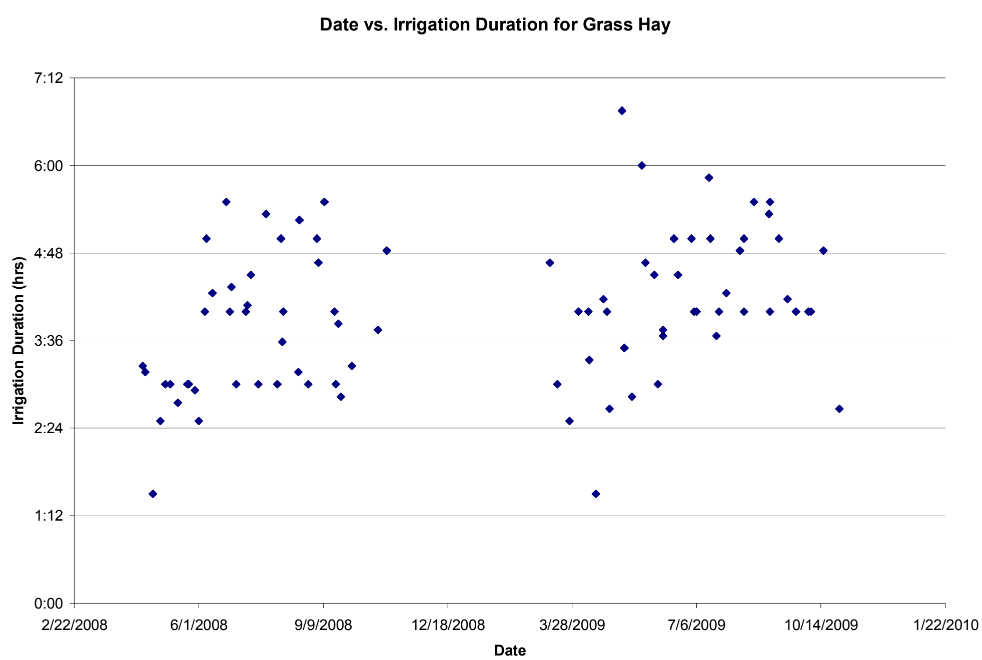


Figure 5.8: Irrigation Duration over Time for Grass Hay Fields

The flow rate values for the grass hay fields were also examined to determine whether any temporal trends were evident. The flow rate values exhibited data scatter similar to the irrigation duration data presented in Figure 5.8, and it was found that no significant trends existed during the 2008 and 2009 irrigation seasons.

The four monitored alfalfa hay fields exhibited mean irrigation duration of eight hours and eight minutes for an average field size of 10.11 acres during the two year study. This amounts to a mean irrigation time of 48 minutes per acre. This value corresponds well with the value found for grass hay fields and MRGCD water policy, which suggests one hour per acre as an appropriate irrigation duration. The average flow rate for the irrigation events on alfalfa hay fields was found to be 8.52 cfs. Table 5.8 presents the irrigation duration and flow rate values for the alfalfa hay fields.

Table 5.8: Irrigation Duration and Flow Rate Values on Monitored Alfalfa Hay Fields in 2008 and 2009

Logger ID	Irrigation Event	Date	Irrigation Duration (hr:min)	Flow Rate (cfs)
1	1	4/14/2008	11:50	3.69
1	2	5/5/2008	18:00	4.11
1	3	6/1/2008	26:00:00	4.19
1	4	6/24/2008	13:20	1.62
1	5	8/6/2008	15:00	2.26
1	6	9/12/2008	12:30	2.78
1	1	4/13/2009	28:20:00	1.10
1	2	5/11/2009	24:30:00	1.66
1	3	6/18/2009	17:30	1.64
1	4	7/20/2009	10:20	1.76
1	5	8/27/2009	26:50:00	0.82
2	1	4/5/2008	9:45	6.70
2	2	4/25/2008	9:48	7.86
2	3	5/23/2008	10:00	9.32
2	4	6/20/2008	10:55	9.64
2	5	7/3/2008	9:20	8.67
2	6	8/6/2008	6:10	7.54
2	7	8/28/2008	13:20	6.67

Logger ID	Irrigation Event	Date	Irrigation Duration (hr:min)	Flow Rate (cfs)
2	8	9/12/2008	12:50	7.63
2	1	3/31/2009	13:20	9.88
2	2	4/30/2009	9:30	6.93
2	3	6/6/2009	9:20	11.07
2	4	7/11/2009	12:00	9.52
2	5	7/23/2009	9:40	9.39
2	6	8/21/2009	14:50	7.80
3	1	5/2/2008	3:15	10.75
3	2	5/23/2008	5:45	10.33
3	3	6/19/2008	5:00	10.76
3	4	8/1/2008	6:40	9.69
3	5	9/4/2008	4:10	8.68
3	6	9/24/2008	4:40	8.70
3	1	4/23/2009	5:50	7.06
3	2	5/11/2009	7:10	10.44
3	3	6/4/2009	5:45	8.21
3	4	7/13/2009	7:45	7.86
3	5	7/29/2009	5:50	7.68
3	6	9/3/2009	7:20	7.06
3	7	10/15/2009	6:30	9.47
6	1	4/22/2008	2:20	10.92
6	2	5/15/2008	2:00	8.55
6	3	5/30/2008	1:45	10.35
6	4	6/12/2008	2:00	5.50
6	5	6/26/2008	1:45	8.89
6	6	7/10/2008	1:40	6.90
6	7	7/27/2008	1:45	4.46
6	8	8/7/2008	1:45	10.63
6	9	8/26/2008	2:00	16.72
6	10	9/11/2008	2:00	14.02
6	11	10/3/2008	3:00	14.23
6	1	3/31/2009	3:30	15.03
6	2	4/18/2009	3:20	10.03
6	3	4/29/2009	3:30	15.29
6	4	5/12/2009	3:30	14.10
6	5	6/4/2009	3:30	15.96
6	6	6/17/2009	3:30	8.43
6	7	7/2/2009	3:30	10.13
6	8	7/20/2009	3:50	12.44
6	9	8/6/2009	4:00	10.66
6	10	8/20/2009	3:30	13.14
6	11	9/8/2009	4:50	9.75
6	12	10/2/2009	4:00	12.54

The irrigation duration and flow rate values for the alfalfa hay fields were also examined to determine whether any temporal trends were evident. The irrigation duration and flow rate values exhibited data scatter similar to the irrigation duration data presented in Figure 5.8 and it was found that no significant trend existed during either the 2008 or 2009 irrigation seasons. There are several reasons why no trends existed for either irrigation duration or flow rate. Irrigation duration is dependent on flow rate, soil type, soil moisture levels in the field, rain events, the height and density of the crop, varying irrigation advance time, and finally the judgment of the irrigator. Flow rate is dependent on how much water is supplied at the heading of an irrigation canal and is determined by a ditch-rider.

For both the grass hay and alfalfa fields the duration and flow rate values are dependent variables. As the flow rate decreases, irrigation duration will increase as less head is available to push the water across a field. Prior to the field study the belief in the MRGCD was that farmers regularly cut each other off by starting an irrigation upstream while a farmer was still irrigating downstream. This results in decreased flow in the ditch downstream and in turn increases the irrigation duration for the downstream farmer. From the collected data and conversations with farmers about each individual irrigation event, it was determined that during the two year study only 11 irrigation events were observed where the head and subsequently the flow rate dropped during an irrigation event due to another farmer cutting in upstream. This represents only 7.6% of all of the monitored irrigation events and sheds light on complaints that the MRGCD has received from farmers. Over the past five years one of the most common complaints this researcher has heard in the MRGCD is that upstream farmers impact irrigation events downstream by cutting in. Based on the collected data it appears that these complaints may be slightly exaggerated. The collected data show that 92.4% of the irrigation events were completed without a drop in flow rate. This indicates that farmers upstream respect downstream farmers and are courteous towards their irrigation needs. The data also indicate that the ditch-riders on the laterals supplying the eight monitored fields scheduled irrigations among different farmers appropriately.

5.2.1.2 Water Applied

Another aspect of irrigation water management that was examined from the collected data was the total water applied during irrigation events. The total water applied for each irrigation event was calculated as a total volume in cubic feet and also as a spatially averaged value of inches per acre. For the monitored grass hay fields the mean volume of water applied per irrigation event was found to be 111,407 cubic feet for a mean acreage of 5.15 acres. The mean application in inches was found to be 5.98 inches. Table 5.9 presents the results from each irrigation event for grass hay.

Table 5.9: Total Water Applied and Depth Applied on Monitored Grass Hay Fields in 2008 and 2009

Logger ID	Irrigation Event	Date	Total Water Applied (ft^3)	Depth Applied (inches)
4	1	4/19/2008	49920	3.13
4	2	5/5/2008	36504	2.29
4	3	5/23/2008	74667	4.67
4	4	6/7/2008	94543	5.92
4	5	6/27/2008	77265	4.84
4	6	7/9/2008	82913	5.19
4	7	8/6/2008	105161	6.58
4	8	8/20/2008	80683	5.05
4	9	9/10/2008	71934	4.50

Logger ID	Irrigation Event	Date	Total Water Applied (ft^3)	Depth Applied (inches)
4	10	9/23/2008	65226	4.08
4	11	10/30/2008	90905	5.69
4	1	3/10/2009	102177	6.40
4	2	4/11/2009	92362	5.78
4	3	4/22/2009	61405	3.84
4	4	5/9/2009	90539	5.67
4	5	5/26/2009	85127	5.33
4	6	6/9/2009	80272	5.03
4	7	7/6/2009	81828	5.12
4	8	7/22/2009	87585	5.48
4	9	8/10/2009	34582	2.17
4	10	9/2/2009	100781	6.31
4	11	9/17/2009	76073	4.76
5	1	4/17/2008	76284	5.75
5	2	5/1/2008	63900	4.82
5	3	5/15/2008	65538	4.94
5	4	5/29/2008	46299	3.49
5	5	6/12/2008	56623	4.27
5	6	6/26/2008	60617	4.57
5	7	7/10/2008	64076	4.83
5	8	7/25/2008	91283	6.88
5	9	8/7/2008	56162	4.23
5	10	8/21/2008	74721	5.63
5	11	9/4/2008	98884	7.45
5	12	9/18/2008	74384	5.61
5	13	10/2/2008	64293	4.85
5	14	10/23/2008	46842	3.53
5	1	3/26/2009	37912	2.86
5	2	4/16/2009	34191	2.58
5	3	5/7/2009	37670	2.84
5	4	5/23/2009	75344	5.68
5	5	6/5/2009	58230	4.39
5	6	6/18/2009	77990	5.88
5	7	7/2/2009	55002	4.15
5	8	7/16/2009	101087	7.62
5	9	7/30/2009	84503	6.37
5	10	8/13/2009	107675	8.12
5	11	9/3/2009	117865	8.88
5	12	9/24/2009	60919	4.59
5	13	10/16/2009	78388	5.91
5	14	10/29/2009	39767	3.00
7	1	4/25/2008	40770	2.50
7	2	5/9/2008	97481	5.99
7	3	6/1/2008	70967	4.36
7	4	6/23/2008	123476	7.58
7	5	7/13/2008	91389	5.61

Logger ID	Irrigation Event	Date	Total Water Applied (ft^3)	Depth Applied (inches)
7	6	8/8/2008	112546	6.91
7	7	9/5/2008	101239	6.22
7	8	9/21/2008	74809	4.59
7	1	4/10/2009	85990	5.28
7	2	4/27/2009	73584	4.52
7	3	5/15/2009	94796	5.82
7	4	6/9/2009	96963	5.96
7	5	7/17/2009	128516	7.89
7	6	8/21/2009	154389	9.48
7	7	9/3/2009	124178	7.63
7	8	10/4/2009	49532	3.04
8	2	5/24/2008	261003	13.68
8	3	6/6/2008	325899	11.10
8	4	7/1/2008	196965	10.32
8	5	7/19/2008	192629	6.56
8	6	8/3/2008	181595	9.52
8	7	8/28/2008	263721	8.98
8	8	9/19/2008	229606	7.82
8	1	3/16/2009	147697	5.03
8	2	4/2/2009	235892	8.03
8	3	4/25/2009	290761	9.90
8	4	6/2/2009	286696	9.76
8	5	6/21/2009	183570	6.25
8	6	7/4/2009	227981	7.76
8	7	7/24/2009	223510	7.61
8	8	8/13/2009	230864	7.86
8	9	9/10/2009	367125	12.50
8	10	10/6/2009	251818	8.58

For the monitored alfalfa hay fields the mean volume of water applied per irrigation event was found to be 196,025 cubic feet for a mean acreage of 10.11 acres. The mean application in inches was found to be 5.38 inches. Table 5.10 presents the results from each irrigation event for alfalfa.

Table 5.10: Total Water Applied and Depth Applied on Monitored Alfalfa Hay Fields in 2008 and 2009

Logger ID	Irrigation Event	Date	Total Water Applied (ft^3)	Depth Applied (inches)
1	1	4/14/2008	157190	6.95
1	2	5/5/2008	266004	7.44
1	3	6/1/2008	325216	9.09
1	4	6/24/2008	149748	4.19
1	5	8/6/2008	150338	4.20
1	6	9/12/2008	125121	3.50
1	1	4/13/2009	112475	3.15
1	2	5/11/2009	148812	4.16
1	3	6/18/2009	173791	4.86
1	4	7/20/2009	113443	3.17
1	5	8/27/2009	130644	3.65
2	1	4/5/2008	235170	5.14
2	2	4/25/2008	275952	6.03
2	3	5/23/2008	341320	7.46
2	4	6/20/2008	387476	8.46
2	5	7/3/2008	296378	6.47
2	6	8/6/2008	171854	3.75
2	7	8/28/2008	324088	7.08
2	8	9/12/2008	357262	7.80
2	1	3/31/2009	480247	10.49
2	2	4/30/2009	240987	5.26
2	3	6/6/2009	371979	8.13
2	4	7/11/2009	416958	9.11
2	5	7/23/2009	332587	7.27
2	6	8/21/2009	421457	9.21
3	1	5/2/2008	125775	3.21
3	2	5/23/2008	217299	5.55
3	3	6/19/2008	200079	5.11
3	4	8/1/2008	238567	6.10
3	5	9/4/2008	135483	3.46
3	6	9/24/2008	151377	3.87
3	1	4/23/2009	152564	3.90
3	2	5/11/2009	269414	6.88
3	3	6/4/2009	177247	4.53
3	4	7/13/2009	221764	5.67
3	5	7/29/2009	165790	4.24
3	6	9/3/2009	190490	4.87
3	7	10/15/2009	272789	6.97
6	1	4/22/2008	101402	5.16
6	2	5/15/2008	76917	3.91
6	3	5/30/2008	68859	3.50
6	4	6/12/2008	44546	2.27

Logger ID	Irrigation Event	Date	Total Water Applied (ft^3)	Depth Applied (inches)
6	5	6/26/2008	40097	2.04
6	6	7/10/2008	45518	2.31
6	7	7/27/2008	32135	1.63
6	8	8/7/2008	76505	3.89
6	9	8/26/2008	130465	6.63
6	10	9/11/2008	109373	5.56
6	11	10/3/2008	162258	8.25
6	1	3/31/2009	198449	6.10
6	2	4/18/2009	126398	3.88
6	3	4/29/2009	201808	6.20
6	4	5/12/2009	186066	5.72
6	5	6/4/2009	210639	6.47
6	6	6/17/2009	111214	3.42
6	7	7/2/2009	133732	4.11
6	8	7/20/2009	179173	5.51
6	9	8/6/2009	159831	4.91
6	10	8/20/2009	173397	5.33
6	11	9/8/2009	175579	5.39
6	12	10/2/2009	188051	5.78

The two mean values for depth applied for grass hay and alfalfa are quite similar with values of 5.98 inches and 5.38 inches, respectively. This is to be expected as all monitored fields were irrigated basins with borders. Overall, these numbers are significantly lower than two previous studies in the MRGCD. The two previous studies found that the mean application depth for an irrigation event was between 7.2 and 10.1 inches (Lundahl, 2006; URS, 2005a) in the MRGCD. The completed study on the eight fields had a much larger scope spanning two years, and therefore it provided a better representation of the mean application depth. The results of the study suggest that the farmers in the MRGCD are better at managing irrigation events and apply far less water per irrigation event than previously thought.

Another aspect of irrigation water application that was examined during this study was the total amount of water applied to each field during the irrigation season. The total depth of water applied during the 2008 and 2009 season was calculated by adding up the depth applied for each individual irrigation event. For the monitored grass hay fields it was found that the mean total water applications were 61.4 and 65.4 inches in 2008 and 2009 respectively. Table 5.11 presents the total inches of water applied for the monitored grass hay fields.

Table 5.11: Total Water Applied for Grass Hay Fields in 2008 and 2009

Logger ID	Crop Type	Total Water Applied 2008 (inches)	Total Water Applied 2009 (inches)
4	Grass Hay	51.9	55.9
5	Grass Hay	70.8	72.8
7	Grass Hay	44.8	49.6
8	Grass Hay	77.9	83.3

For the monitored alfalfa hay fields it was found that the mean total water applications were 40.0 and 42.1 inches in 2008 and 2009 respectively. Table 5.12 present the total inches of water applied for the monitored alfalfa hay field.

Table 5.12: Total Water Applied for Grass Hay Fields in 2008 and 2009

Logger ID	Crop Type	Total Water Applied 2008 (inches)	Total Water Applied 2009 (inches)
1	Alfalfa Hay	35.4	19.0
2	Alfalfa Hay	52.2	49.5
3	Alfalfa Hay	27.3	37.1
6	Alfalfa Hay	45.2	62.8

The data for water applied shows that the total depth of water applied to grass hay fields was significantly higher than for the alfalfa fields. In 2008 the mean grass hay application was 21 inches higher than alfalfa and in 2009 it was 23.3 inches higher. The main reason for this difference can be attributed to the shorter root zone of grass hay. Since grass hay has a shorter root zone, it requires more frequent irrigation with a smaller application depth. Since the fields in this study were basins it was not possible for farmers to apply an appropriately small irrigation depth. Therefore, the difference between the grass hay and alfalfa hay application depths represents the depth of water necessary to complete an irrigation event, even though not all of the water was stored in the crop root zone.

Overall, the values of total water depth applied found during the study indicate that farmers in the MRGCD may be more frugal in water application than once believed. The only previously conducted study that examined total application depth during an irrigation season found that 100 inches was a representative application depth (Lundahl, 2006). The mean values across both years of 63.4 inches for grass hay and 41.1 inches for alfalfa hay were both significantly lower than the previously determined 100 inches, which suggests that farmers apply considerably less water.

5.2.1.3 Application Efficiency

The overall analysis of on farm application efficiency regardless of crop type for use in the DSS model, is presented in Section 5.1.3. This analysis found that the mean application efficiency for the 2008 season was 45% for 71 monitored irrigation events on the eight instrumented fields. For the 2009 irrigation season the mean application efficiency was found to be 44% for 73 irrigation events.

From the collected data it was also possible to refine the analysis of on farm application efficiency. First, the application efficiency was separated by crop type as analysis of the total water applied during an entire season suggested that fields with alfalfa hay would have higher application efficiency.

The mean value of application efficiency for each grass field was calculated for the 2008 and 2009 irrigation seasons from all irrigation events. For 2008 the application efficiencies covered a range from 31% to 50%. For 2009 the application efficiency covered a range from 22% to 52%. The mean application efficiency of all 40 grass hay irrigation events was found to be 40.8% in 2008. The mean application efficiency of all 43 grass hay irrigation events was found to be 38.6% in 2009. Table 5.13 displays the average values found for each individual grass field.

Table 5.13: Mean Application Efficiency for Grass Hay Fields in 2008 and 2009

Logger ID	Crop Type	Application Efficiency 2008	Application Efficiency 2009
4	Grass Hay	50%	52%
5	Grass Hay	44%	41%
7	Grass Hay	33%	36%
8	Grass Hay	31%	22%

The mean value of application efficiency for each alfalfa field was also calculated for the 2008 and 2009 irrigation seasons for all irrigation events. For 2008 the application efficiencies covered a range from 29% to 82%. For 2009 the application efficiency covered a range from 23% to 85%. The mean application efficiency of all 31 alfalfa hay irrigation events was found to be 50.2% in 2008. The mean application efficiency of all 30 alfalfa hay irrigation events was found to be 52.5% in 2009. Table 5.14 displays the average values found for each individual alfalfa field.

Table 5.14: Mean Application Efficiency for Alfalfa Hay Fields in 2008 and 2009

Logger ID	Crop Type	Application Efficiency 2008	Application Efficiency 2009
1	Alfalfa Hay	49%	66%
2	Alfalfa Hay	29%	23%
3	Alfalfa Hay	82%	85%
6	Alfalfa Hay	45%	43%

The results show that the mean application efficiency for the alfalfa fields was 9.4% higher than the grass hay fields in 2008 and 13.9% higher in 2009. The temporal variation of the application efficiency numbers was also examined but no useful trends could be identified. Overall, the application efficiency numbers obtained during the study indicate that farmers in the MRGCD are close to the average application efficiency that is to be expected for basin irrigation.

5.2.1.4 Irrigation Interval

Using the collected data it was also possible to determine the irrigation interval utilized by farmers in the MRGCD. Throughout this section irrigation interval is defined as the number of days between irrigation events.

The mean value of irrigation interval for each grass field was calculated for the 2008 and 2009 irrigation seasons from all irrigation events. For 2008 the mean irrigation interval covered a range from 14.5 to 21.3 days. For 2009 the mean irrigation interval covered a range from 16.7 to 25.3 days. The mean irrigation interval of all 40 grass hay irrigation events was found to be 18.1 days in 2008. The mean irrigation interval of all 43 grass hay irrigation events was found to be 20.2 days in 2009. These irrigation interval numbers are quite similar to the MRGCD recommended 21 day irrigation interval Table 5.15 displays the average values found for each individual grass field.

Table 5.15: Mean Irrigation Interval for Grass Hay Fields in 2008 and 2009

Logger ID	Crop Type	Average Irrigation Interval 2008 (days)	Average Irrigation Interval 2009 (days)
4	Grass Hay	19.4	19.1
5	Grass Hay	14.5	16.7
7	Grass Hay	21.3	25.3
8	Grass Hay	19.7	22.7

The mean value of irrigation interval for each alfalfa field was calculated for the 2008 and 2009 irrigation seasons from all irrigation events. For 2008 the mean irrigation interval covered a range from 16.4 to 30.2 days. For 2009 the mean irrigation interval covered a range from 16.8 to 34.0 days. The mean irrigation interval of all 31 alfalfa hay irrigation events was found to be 23.0 days in 2008. The mean irrigation interval of all 30 alfalfa hay irrigation events was found to be 24.6 days in 2009. These irrigation interval numbers are slightly longer than the MRGCD recommended 21 day irrigation interval. Table 5.16 displays the mean values found for each individual alfalfa field.

Table 5.16: Mean Irrigation Frequency for Alfalfa Hay Fields in 2008 and 2009

Logger ID	Crop Type	Average Irrigation Interval 2008 (days)	Average Irrigation Interval 2009 (days)
1	Alfalfa Hay	30.2	34.0
2	Alfalfa Hay	22.9	28.6
3	Alfalfa Hay	29.0	29.2
6	Alfalfa Hay	16.4	16.8

The results show that the mean irrigation interval for the alfalfa fields was 4.9 days longer than for grass hay fields in 2008 and 4.4 days longer in 2009. This difference is to be expected and accounts for the physiological differences between the two crops. Alfalfa is a drought tolerant crop that has a deep root depth which allows the crop to utilize a greater soil volume to extract moisture. Trends over time did not exist for irrigation interval. The most likely reason for this is that most farmers in the MRGCD try to irrigate on a set schedule or when the water is available to the ditch-rider.

5.2.2 Crop Yield

In addition to characterizing farmers irrigation practices the yields of the eight monitored fields were also determined in 2008 and 2009. This was done to elucidate yield numbers in the MRGCD. This was accomplished by closely monitoring the eight fields and coordinating with the farmers about cutting and bailing events. Once a farmer had cut and bailed a field, the total number of bails were counted using the bail counters on the farmer's bailer or by manually counting the bails in the field. To get an average weight of the bails ten bails were selected at random throughout the field and weighed. This was done for every cutting event on each of the eight fields during the two year study. The average weight determined from weighing the ten bails was multiplied by the total number of bails counted resulting in a total weight for the cutting for the monitored field. This number was divided by the acreage of the field to give a yield in tons per acre. The values for all the cuttings during the year were summed resulting in the total yield in tons per acre per year.

The yields for grass hay varied between 2.4 and 7.4 tons/acre in 2008. In 2009 the yield numbers for grass hay varied between 1.4 and 8.1 tons/ acre. For the monitored grass hay fields the mean tons per acre per year were calculated to be 4.4 tons/acre in 2008 and 3.9 tons/acre in 2009. Table 5.17 displays the yield numbers found for grass hay.

Table 5.17: Yield for Grass Hay Fields in 2008 and 2009

Logger ID	Crop Type	2008 Yield (tons/acre)	2009 Yield (tons/acre)
4	Grass Hay	7.4	8.1
5	Grass Hay	5.3	4.7
7	Grass Hay	2.4	1.4
8	Grass Hay	2.4	1.5

The yields for alfalfa hay varied between 2.6 and 8.2 tons/acre in 2008. In 2009 the yield numbers for alfalfa hay varied between 3.8 and 9 tons/acre. For the monitored alfalfa hay fields the mean tons per acre per year were calculated to be 5.0 tons/acre in 2008 and 5.9 tons/acre in 2009. Table 5.18 displays the yield numbers found for alfalfa hay.

Table 5.18: Yield for Alfalfa Hay Fields in 2008 and 2009

Logger ID	Crop Type	2008 Yield (tons/acre)	2009 Yield (tons/acre)
1	Alfalfa Hay	5.9	6.2
2	Alfalfa Hay	2.6	4.8
3	Alfalfa Hay	8.2	9.0
6	Alfalfa Hay	3.2	3.8

The results show that the farmers on fields 1, 3, and 4 had the highest yield numbers in both years. The farmers on fields 1, 3, and 4 intensively manage their fields and farm at a commercial level, while the other farmers use less intensive farm management.

The results also show that the mean yield for the alfalfa fields was 0.6 tons/acre higher than the grass hay fields in 2008 and 2 tons/acre higher in 2009. The fact that the alfalfa yields were higher than the grass hay yields in both years makes physical sense as alfalfa yields are generally higher than grass hay yields. The increased difference in yields between the two crops in 2009 also makes physical sense. In 2008, the spring weather was uncharacteristically cold and alfalfa stayed dormant, which resulted in some farmers performing their first cutting as late as the beginning of June. For the seasonal totals the cold weather at the beginning of the reason resulted in farmers having one less cut than in normal years. In 2009 the spring weather was characteristic of central New Mexico and farmers were cutting their alfalfa by the middle of May.

There are many reasons for the extreme variations found both in the alfalfa and grass hay yield numbers. Farm yields depend on many factors such as fertilizer application rates, fertilizer types used, fertilizer costs, and the age of the planted field. During the 2008 and 2009 irrigation season, the farmer on field number six lost most of his first cutting to geese feeding on his sprouting alfalfa. Another factor observed in the MRGCD was that rain events reduced alfalfa yields due to the necessary raking, which breaks the leaves off the stems. Even with all of the variables that can affect farm yield, the farmers in the MRGCD appear to be obtaining high yield numbers when they apply the appropriate fertilizer and manage their fields intensively.

The yield obtained during the two years for both crops was also linked to the water applied. Although there is no unique crop water production function (yield vs. applied water) due to variables such as fertilizer application and soil types, curves of this type can still be beneficial for farmers and water managers in the MRGCD. The curves were developed by combining the collected data for the 2008 and 2009 irrigation seasons for both crop types. Once the data were combined, regression equations were applied to find the most appropriate relationship. The most appropriate regression equation was selected using the coefficient of determination as a criterion.

For the grass hay yield and applied water data the most appropriate regression equation was a second order polynomial equation. The coefficient of determination was found to be 0.59. For alfalfa hay yield and applied water data the most appropriate regression equation was also a second order polynomial equation. The coefficient of determination was found to be 0.47. The developed crop yield and applied water curves as well as equations are presented in Figure 5.9 for grass hay and Figure 5.10 for alfalfa hay. It is the hope of this researcher that these curves will be useful to the MRGCD and farmers in the Middle Rio Grande Valley. In the future, research should be conducted to refine these curves by including variables such as fertilizer application and conducting a yield study on a much larger scale.

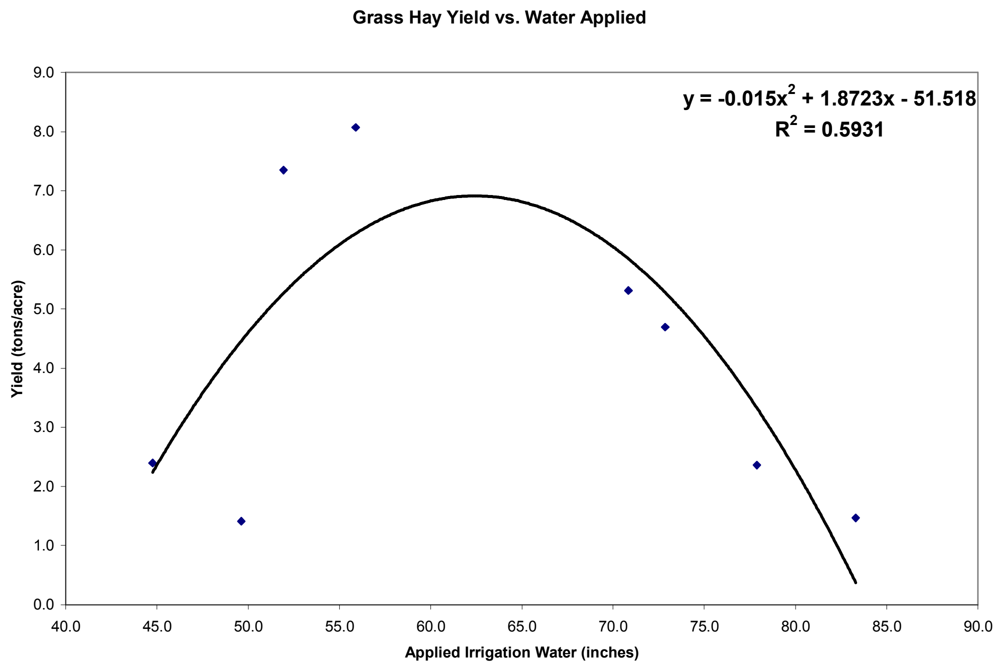


Figure 5.9: Yield and Water Applied Relationship for Grass Hay

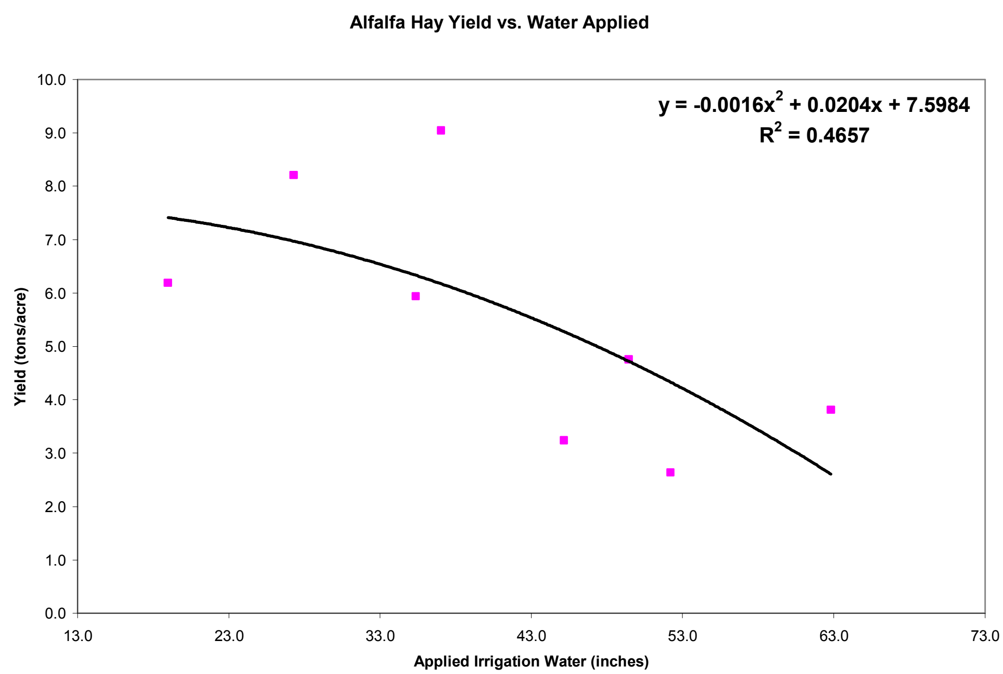


Figure 5.10: Yield and Water Applied Relationship for Alfalfa Hay

5.3 VALIDATION OF PROGRAMMING LOGIC

A key component of validating the DSS and verifying the hypothesis that a DSS can be used to developed real time water delivery schedules based on crop demand was examining the programming logic. This was done by examining the model formulation to ensure that calculations performed by the DSS were correct and by comparing DSS model crop depletions to actual crop depletions measured during the field study. The following two subsections describe the validation of the programming logic.

5.3.1 Examining Model Formulation

The first step in validating the programming logic was to examine the model formulation of the DSS to ensure that the DSS represented canal seepage loss, the depletion of RAM by crops and irrigation interval, the total RAM capacity, and drain return flow. The validation consisted of manually calculating values for the above parameters and comparing these values to the calculations performed using the DSS.

5.3.1.1 Canal Seepage Loss

In order to validate the canal seepage loss calculations performed by the DSS a simplified schematic was created using the Algodones Lateral portion of the Albuquerque Schematic. The Algodones Lateral was separated from the schematic and supplied with an inflow node that had a maximum flow capacity of 100 cfs. The service area for the Algodones Lateral was augmented by adding 1000 acres of alfalfa to the cropped acreage to insure that a significant demand existed to continuously call for a water delivery of the maximum canal capacity. The CIR data used for the validation was from the ET Toolbox and 2005 CIR was used for the crop demand in the validation schematic. The schematic developed for the validation of canal seepage loss calculations is displayed in Figure 5.11.

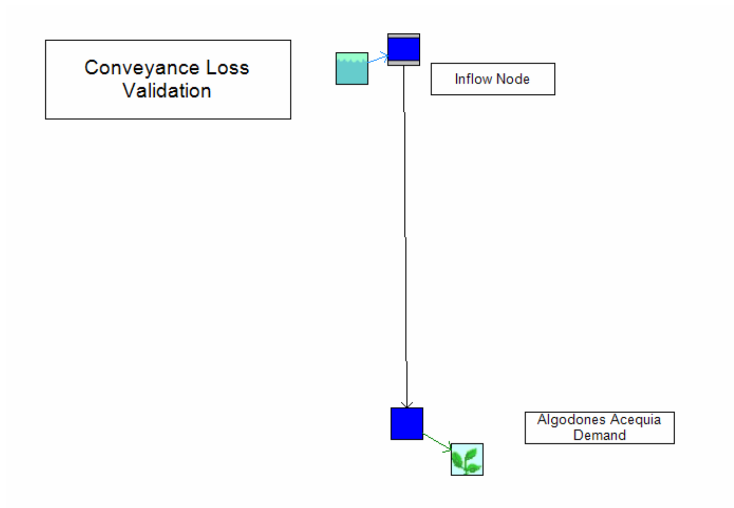


Figure 5.11: Schematic for Validating Canal Seepage Loss Calculations

Using the simplified schematic it was possible to run the model for the 2005 irrigation season in the planning mode. With the developed schematic the inflow node was always calling for the maximum flow due to the high crop demand and was deemed suitable for analyzing the seepage loss for the system.

In order to analyze the seepage loss calculations performed by the DSS, manual calculations were first completed using Microsoft Excel. The manual calculations consisted of determining the expected conveyance loss of the canal conveying 100 cfs in the schematic for lengths of 1, 2, 3, 4, 5, 10, 20, 30, 50, and 100 miles. The conveyance loss was calculated for the aforementioned lengths for three conveyance loss rates of 1.5%, 3%, and 4.5% per mile. The theoretical water available at the end of the canal for the Algodones Lateral was then determined by subtracting the loss from the 100 cfs entering the canal. Once the manual calculations were completed, the DSS was run using the varying canal seepage scenarios by changing the canal length and seepage loss rates in the canal connection summary.

The DSS was run a total of 30 times to achieve a seepage loss value and a value for the water available for the Algodones Lateral for each of the lengths and seepage loss rates. The results of the analysis are displayed in Tables 5.19, 5.20 and 5.21.

Table 5.19: Results of Seepage Loss Rate Validation at 1.5% per mile

Stream Length (Miles)	Conveyance Loss (% per mile)	Theoretical Water Available (cfs)	DSS Model Water Available (cfs)
1	1.5	98.50	98.50
2	1.5	97.02	97.02
3	1.5	95.57	95.57
4	1.5	94.13	94.13
5	1.5	92.72	92.72
10	1.5	85.97	85.97
20	1.5	73.91	73.91
30	1.5	63.55	63.55
50	1.5	46.97	46.97
100	1.5	22.06	22.06

Table 5.20: Results of Seepage Loss Rate Validation at 3% per mile

Stream Length (Miles)	Conveyance Loss (% per mile)	Theoretical Water Available (cfs)	DSS Model Water Available (cfs)
1	3	97.00	97.00
2	3	94.09	94.09
3	3	91.27	91.27
4	3	88.53	88.53
5	3	85.87	85.87
10	3	73.74	73.74
20	3	54.38	54.38
30	3	40.10	40.10
50	3	21.81	21.81
100	3	4.76	4.76

Table 5.21: Results of Seepage Loss Rate Validation at 4.5% per mile

Stream Length (Miles)	Conveyance Loss (% per mile)	Theoretical Water Available (cfs)	DSS Model Water Available (cfs)
1	4.5	95.50	95.50
2	4.5	91.20	91.20
3	4.5	87.10	87.10
4	4.5	83.18	83.18
5	4.5	79.44	79.44
10	4.5	63.10	63.10
20	4.5	39.82	39.82
30	4.5	25.12	25.12
50	4.5	10.00	10.00
100	4.5	1.00	1.00

For the completed analysis the theoretical water available and the water available calculated using the DSS were exactly the same for the 30 tested scenarios. The completed analysis indicates that the DSS correctly calculates canal seepage loss across a range of canal lengths and conveyance loss rates.

5.3.1.2 RAM Depletion

In order to validate the RAM depletion calculations performed by the DSS another simplified schematic was created. Two crops were used for this exercise, namely pasture and alfalfa, which were added to the demand nodes of CSU 1 and CSU 2, respectively. Figure 5.12 displays the schematic developed for validating the RAM depletion calculations.

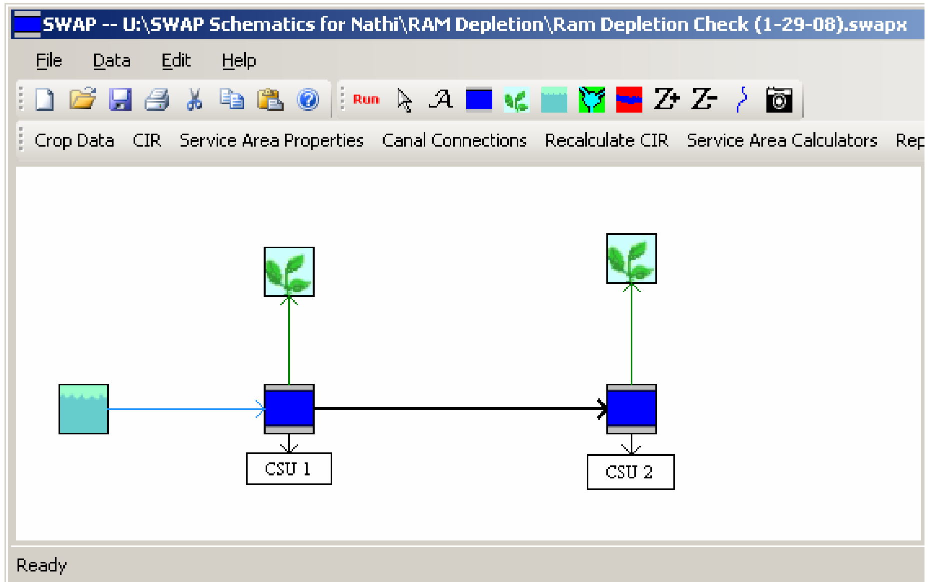


Figure 5.12: Schematic Developed for Validating RAM Depletion Calculations

The available holding water capacity (AWC) was set at 2 in/ft up to a depth of 6 ft. The rooting depth for pasture was 4 ft and 5 ft for alfalfa. The crop irrigation requirements (CIR) per month were set at 5 inches for alfalfa and 4 inches for pasture and were set using the user-defined CIR function in the DSS. The flow rate for the canal was 30 cfs, with application efficiency of 75%, and a total canal length of 0.6 miles. The maximum allowable depletion (MAD) for pasture and alfalfa was 45% and 60% respectively, and the area of the planted acreage was 250 acres for pasture (Demand node CSU 1) and 250 acres for alfalfa (Demand node CSU 2).

A database file containing the CIR for the two crops was created and was uploaded to the DSS. The DSS was run and the daily evapotranspiration (ET) of the crops in ac-ft was determined for the demand nodes of CSU 1 and CSU 2.

To check the readily available moisture (RAM) depletion calculated using the DSS, the DSS was run using the input parameters described previously. The DSS was run in planning mode and the output selected for the schedule was RAM remaining in ac-ft. The data for the entire season for both CSU 1 and CSU 2 was exported into a Microsoft Excel file. The depletion of RAM on a daily basis was calculated in Excel by deducting the daily ET from the RAM for both CSU 1 and CSU 2 demand nodes. The results of the DSS depletion and the manual calculations for the period from the entire month of March are shown in Table 5.22 for both demand nodes. Only days in March are presented because the results for the remainder of the year were identical. The green cells in the Table 5.22 represent irrigation events where the RAM was replenished.

The completed analysis indicates that the DSS RAM depletion and the calculated theoretical depletion are the same. Using the user defined CIR, the depletion patterns in RAM using the DSS or manual calculations are identical. This indicates that the calculations of RAM depletion performed by the DSS are correct.

Table 5.22: Results of RAM Depletion Validation

	CSU1 (Pasture)		CSU2 (Alfalfa)	
Date	DSS Model RAM (ac-ft)	Theoretical RAM (ac-ft)	DSS Model RAM (ac-ft)	Theoretical RAM (ac-ft)
3/1	0		0	
3/2	27.1		26.4	
3/3	54.1		52.8	
3/4	75		79.2	
3/5	72.3	72.3	105.6	
3/6	69.6	69.6	125	
3/7	66.9	66.9	121.6	121.6
3/8	64.2	64.2	118.3	118.2
3/9	61.6	61.5	114.9	114.9
3/10	58.9	58.9	111.6	111.5
3/11	56.2	56.2	108.2	108.2
3/12	53.5	53.5	104.8	104.8
3/13	50.8	50.8	101.5	101.4
3/14	48.1	48.1	98.1	98.1
3/15	45.4	45.4	94.8	94.7
3/16	42.7	42.7	91.4	91.4
3/17	40.1	40.0	88	88.0
3/18	37.4	37.4	84.7	84.6
3/19	34.7	34.7	81.3	81.3
3/20	32	32.0	78	77.9
3/21	29.3	29.3	74.6	74.6
3/22	26.6	26.6	71.2	71.2
3/23	23.9	23.9	67.9	67.8
3/24	21.2	21.2	64.5	64.5
3/25	18.5	18.5	61.2	61.1
3/26	15.9	15.8	57.8	57.8
3/27	13.2	13.2	54.4	54.4
3/28	10.5	10.5	51.1	51.0
3/29	7.8	7.8	47.7	47.7
3/30	5.1	5.1	44.4	44.3
3/31	2.4	2.4	41	41.0

5.3.1.3 Total RAM Capacity

To validate that the DSS calculated the total RAM capacity correctly the Rinconada Lateral demand node in the Socorro Schematic was examined. To ensure that the DSS calculations were correct they were compared to theoretical calcaultions. The crop used for the validation was alfalfa with a rooting depth of 5 ft. The crop takes 75 days to grow to full cover and has a maximum allowable depletion (MAD) of 60%. Table 5.23 shows the soil characteristics and the acreage of the crop from 2003 until 2008 on the Rinconada Lateral.

Table 5.23: Soil Characteristics and Acreages of the Rinconada Lateral used for Validation

Soil Characteristics

AWC (in/ft)	1 ft	2 ft	3 ft	4 ft	5 ft	6 ft
	1.03	0.98	0.97	0.96	0.95	0.95

Acreage

Crop/Year	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**
Alfalfa	74.83	85.4	11.91	11.91	11.91	11.91

For the manual calculation of RAM in ac-ft, the following formula was used,

$$RAM = (AWC/12) * RD * Area * MAD$$

Where: RAM = readily available water (ac-ft)
AWC = available water holding capacity (in/ft)
RD = rooting depth (ft)
Area = acreage of crop planted (acres)
MAD = maximum allowable deficit (%), and
12 is a constant for converting inches to feet

For the AWC the average of 5 ft depth was used. The average AWC was 0.978 in/ft. Next, a spreadsheet was created to manually calculate the theoretical RAM capacity. The values were calculated using the presented equation. The next step was to run the DSS and determine the RAM available. Once this was completed the data from the DSS was exported into the spreadsheet for comparison. Table 5.24 displays the results of the comparison between theoretical RAM capacity and DSS model RAM capacity.

Table 5.24: Results of Total RAM Capacity Validation

Theoretical RAM Capacity (Ac-Ft)

Year	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
2003	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30
2004	20.88	20.88	20.88	20.88	20.88	20.88	20.88	20.88
2005	2.91	2.91	2.91	2.91	2.91	2.91	2.91	2.91
2006	2.91	2.91	2.91	2.91	2.91	2.91	2.91	2.91
2007	2.91	2.91	2.91	2.91	2.91	2.91	2.91	2.91
2008	2.91	2.91	2.91	2.91	2.91	2.91	2.91	2.91

DSS Model RAM Capacity (Ac-Ft)

Year	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
2003	18.30	18.30	18.30	18.30	18.30	18.30	18.30	18.30
2004	20.88	20.88	20.88	20.88	20.88	20.88	20.88	20.88
2005	2.91	2.91	2.91	2.91	2.91	2.91	2.91	2.91
2006	2.91	2.91	2.91	2.91	2.91	2.91	2.91	2.91
2007	2.91	2.91	2.91	2.91	2.91	2.91	2.91	2.91
2008	2.91	2.91	2.91	2.91	2.91	2.91	2.91	2.91

The same analysis was also performed on the Vasquez Lateral in the Socorro schematic and yielded the same results. For the completed analysis the calculated theoritical RAM capacity values were exactly the same as the DSS calculated RAM capacity. The completed analysis for the Rincoda and Vasquez laterals indicates that the model correctly calculates the total RAM capacity.

5.3.1.4 Drain Return Flow

In order to validate the calculations of return flow in the DSS, drains were added to the schematic that was developed for examining RAM depletions (Figure 5.12). The characteristics of the drains were set that all return flow occurred on the day following irrigation. The theoretical flows in CSU 1 Drain and CSU 2 Drain were calculated manually utilizing Microsoft Excel. The flow to irrigation was set as 30 cfs for node CSU 1 and 20 cfs for node CSU 2. The theoretical flow was calculated for return flow efficiencies of 0%, 25%, 50%, 75% and 100% and application efficiencies of 25%, 50%, and 75% for both nodes. The DSS was then run a total of 15 times with the return flow efficiency and application efficiency being varied for each specific comparison. The results from the scheduler for flow in canal were recorded for each drain and each specific DSS model run. The results of the drain return flow analysis are displayed in Table 5.25.

Table 5.25: Results of Drain Return Flow Validation

75% Application Efficiency

Flow to Irrigation (CSU 1)	Return Flow Percentage	Theoretical Return Flow (cfs)	DSS Model Return Flow (cfs)
30	100.00%	7.5	7.5
30	75.00%	5.6	5.6
30	50.00%	3.8	3.8
30	25.00%	1.9	1.9
30	0.00%	0	0

Flow to Irrigation (CSU 2)	Return Flow Percentage	Theoretical Return Flow (cfs)	DSS Model Return Flow (cfs)
20	100.00%	5	5
20	75.00%	3.8	3.8
20	50.00%	2.5	2.5
20	25.00%	1.3	1.3
20	0.00%	0	0

50% Application Efficiency

Flow to Irrigation (CSU 1)	Return Flow Percentage	Theoretical Return Flow (cfs)	DSS Model Return Flow (cfs)
30	100.00%	15	15
30	75.00%	11.3	11.3
30	50.00%	7.5	7.5
30	25.00%	3.8	3.8
30	0.00%	0	0

Flow to Irrigation (CSU 2)	Return Flow Percentage	Theoretical Return Flow (cfs)	DSS Model Return Flow (cfs)
20	100.00%	10	10
20	75.00%	7.5	7.5
20	50.00%	5	5
20	25.00%	2.5	2.5
20	0.00%	0	0

25% Application Efficiency

Flow to Irrigation (CSU 1)	Return Flow Percentage	Theoretical Return Flow (cfs)	DSS Model Return Flow (cfs)
30	100.00%	22.5	22.5
30	75.00%	16.9	16.9
30	50.00%	11.3	11.3
30	25.00%	5.6	5.6
30	0.00%	0	0

Flow to Irrigation (CSU 2)	Return Flow Percentage	Theoretical Return Flow (cfs)	DSS Model Return Flow (cfs)
20	100.00%	15	15
20	75.00%	11.3	11.3
20	50.00%	7.5	7.5
20	25.00%	3.8	3.8
20	0.00%	0	0

For the completed analysis the theoretical drain flow available and the actual drain flow available calculated using the DSS were exactly the same for the 15 tested scenarios. The completed analysis indicates that the DSS correctly calculates drain flow across a range of return flow efficiencies and application efficiencies

Overall, the calculations performed by the DSS matched the calculations performed manually. The parameters of canal seepage loss, RAM depletion, total RAM capacity, and drain return flow all showed agreement between manual calculations and the DSS calculated values. From the completed analysis it can be summarized that the DSS correctly calculates canal seepage loss, RAM depletion, total RAM capacity, and drain return flow.

5.3.2 Evaluating DSS Model ET and Actual ET

The modeled soil moisture depletion by growing crops in the DSS was an important factor that needed to be verified by field experimentation. In the DSS model, the soil moisture depletions are calculated by using the weather-based Penman-Monteith crop ET equation. To evaluate how well the DSS modeled the crop evapotranspiration, the model calculated values were compared to measurements from the instrumented fields to assess the accuracy of the DSS. During the 2008 and 2009 irrigation seasons, soil moisture sensors were installed in the eight irrigated fields that were selected for the water application efficiency study. The instrumentation of the study fields is described in detail in Appendix F. The data collected for all eight study fields consisted of the volumetric water content collected every 60 minutes at 8 inches and 24 inches of root zone depth. Since the DSS calculates ET from 12:00 AM to 12:00 AM, only the measurements collected at midnight were used to compare the depletion over a 24 hour period. Figure 5.13 displays an example graph of the collected depletion data for Field 5 in 2008.

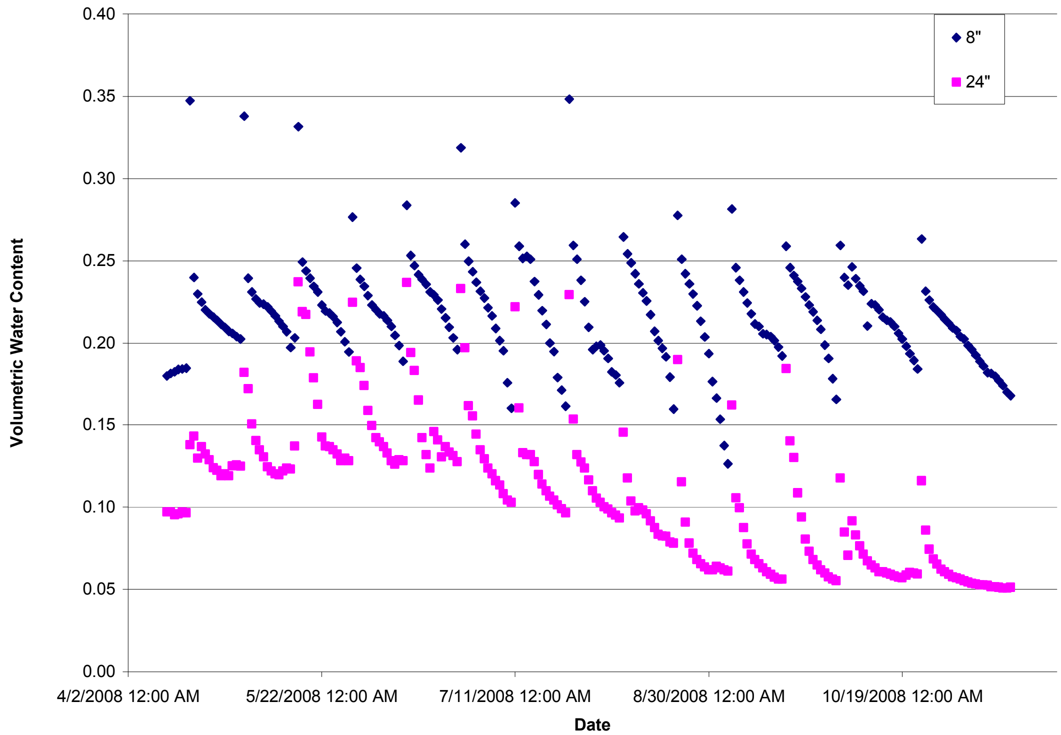


Figure 5.13: Example Graph of the Collected Depletion Data for Field 5 in 2008

The collected data allowed for the creation of a daily water balance for each field to determine the actual evapotranspiration. Since each field contained only two sensors, the depletion from ET could only be calculated between the volumetric water content at field capacity and the volumetric water content directly before the next irrigation. The reason that this methodology was chosen was due to the lack of a deeper sensor that could have been used to determine drainage. During this analysis it was also observed that several of the measured fields had groundwater influence that was observed visually in the graphs of the depletion patterns. For these fields the sensor data collected at 24 inches did not significantly decrease throughout the season and displayed values that were indicative of saturation. Once the ET values for these fields were calculated, they were found to be extremely low. This indicates that groundwater was a source contributing to ET that we could not measure with our limited sensor setup. The setup of the sensors was such that a water balance could not be established when groundwater influence was observed, and the measurements showing influence of groundwater were not used in the evaluation of the DSS ET. This resulted in a total of eight seasonal measurements that could be utilized to validate the DSS.

To calculate the daily ET from each field in inches the 8 inch sensor was deemed to be representative of the first 16 inches of root depth for both the alfalfa and grass hay fields. The 24 inch sensor was chosen to represent the subsequent 20 inches of root depth for grass hay and the subsequent 32 inches for alfalfa. For grass hay and alfalfa this represented a 36 inch and 48 inch effective total root zone, respectively. These values were chosen based on 12 years of research conducted by Garcia et al. (2008) at the NRCS, which was conducted in the Middle Rio Grande and Mesilla Valleys to determine the root depths that were effectively able to utilize and deplete soil moisture. The total daily ET was calculated using the volumetric water content readings at midnight shown in Equation 5.6 displayed below.

$$[(FC_{8"} - WP_{8"})*RZ_{\text{represented by 8" sensor}} + (FC_{24"} - WP_{24"})*RZ_{\text{represented by 24" sensor}}] \quad \textbf{Eq 5.6}$$

The next step in the evaluation of DSS model accuracy consisted of using the DSS to calculate the daily ET values for each of the measured fields so a direct comparison could be conducted. The DSS ET values were calculated for the respective crop of the measured field, either grass hay or alfalfa. The ET values were obtained for the lateral service area that the measured field was in to ensure that spatial variability was addressed and that the DSS modeled ET represented the field location accurately. The modeled values of ET were corrected using an ET correction factor of 0.8 that is currently used in the DSS. This correction factor was determined during a sensitivity analysis of the DSS in 2008 (NMISC, 2008). Initially the model ET and the measured ET were compared on a daily basis. Through this analysis it was observed that the measured daily values showed much more variability than the predicted values using the DSS. Figure 5.14 displays the variability between the measured daily ET and the calculated DSS daily ET for Field 5 in 2008. The variability in Figure 5.14 was characteristic of the eight seasonal ET measurements used for the evaluation of the DSS.

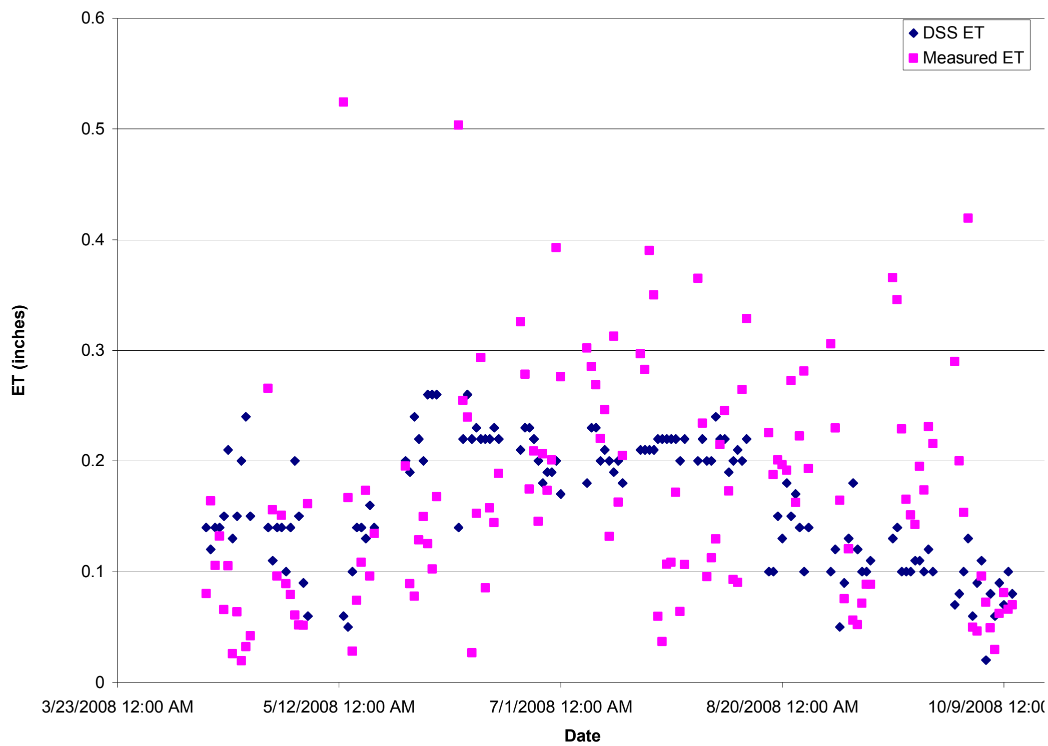


Figure 5.14: Variability in Measured Daily ET Compared to DSS Predicted Daily ET for Field 5 in 2008.

Since the DSS creates schedules that generally have a two week period between irrigation water deliveries, it was deemed appropriate to compare the cumulative measured ET to the cumulative DSS modeled ET to eliminate the daily variability. Cumulative ET has been used by other researchers to validate predictive models and address the inherent variability in measured daily ET values (DeJonge et al. In Review; Vanclooster and Boesten, 2000; Evett and Lascano, 1993: Stroosnijder, 1987; Boesten and Stoosnijder, 1986).

It was found that the measured daily cumulative ET and the DSS predicted daily cumulative ET corresponded well for the eight yearly ET measurements without groundwater influence. Figure 5.15 displays a graph of the cumulative seasonal ET for both the measured and DSS values for Field 5 in 2009. The other seven comparisons showed similar results to Figure 5.15.

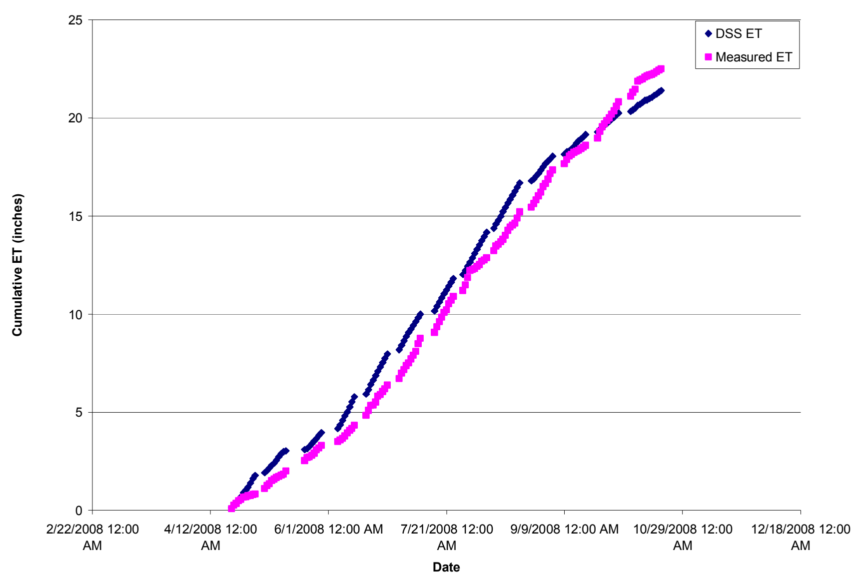


Figure 5.15: Measured and DSS Predicted Cumulative Seasonal ET for Field 5 in 2008

Since the measured daily cumulative ET and the DSS predicted daily cumulative ET were similar and displayed nearly identical slopes for all eight seasonal measurements it was decided to compare the measured and predicted cumulative ET values utilizing the Nash-Sutcliffe modeling efficiency statistic. The Nash-Sutcliffe model evaluation statistic was first used to compare hydrologic models (Nash and Sutcliffe, 1970). However, it has since been used to evaluate agricultural models (DeJonge et al. In Review), and is widely used to validate various moisture accounting models (McCuen et al. 2006; Downer and Ogden 2004; Birikundavyi et al. 2002). The Nash-Sutcliffe modeling efficiency statistic is also recommended by ASCE (ASCE, 1993) for evaluation of moisture accounting models. The Nash-Sutcliffe model efficiency statistic is defined in Equation 5.7.

$$E = 1 - \frac{\sum_{t=1}^{T}\left(Q_o^t - Q_m^t\right)^2}{\sum_{t=1}^{T}\left(Q_o^t - \overline{Q_o}\right)^2}$$

Eq 5.7

In this equation Q_o is an actual measurement, Q_m is the model predicted value, and Q_o^t is actual measurement at time t. Nash–Sutcliffe efficiencies can range from $-\infty$ to 1. An efficiency of one ($E = 1$) corresponds to a perfect match of modeled values to the observed data. An efficiency of zero ($E = 0$) indicates that the model predictions are as accurate as the mean of the observed data. An efficiency less than zero ($E < 0$) occurs when the observed mean is a better predictor than the model or, in other words, when the residual variance (described by the nominator in the expression above), is larger than the data variance (described by the denominator). The closer the Nash-Sutcliffe model efficiency is to one, the more accurate the model (Moriasi et al. 2007; Nash and Sutcliffe, 1970). In general, a Nash-Sutcliffe value of 0.70 indicates that a model can adequately predict measured values.

The Nash-Sutcliffe modeling efficiency was calculated for all eight fields with valid ET measurements utilizing the measured daily cumulative ET and the DSS predicted daily cumulative ET. Table 5.26 displays the calculated Nash-Sutcliffe modeling efficiencies.

Table 5.26: Nash-Sutcliffe Modeling Efficiency for Measured Daily Cumulative ET and the DSS Predicted Daily Cumulative ET

Field	Crop	Year	Nash-Sutcliffe Modeling Efficiency
3	AH	2008	**0.94**
3	AH	2009	**0.97**
4	GH	2009	**0.99**
5	GH	2008	**0.98**
5	GH	2009	**0.52**
6	AH	2009	**0.54**
8	GH	2008	**0.98**
8	GH	2009	**0.95**

The analysis of the Nash-Sutcliffe model accuracy statistic indicates that the DSS predicts depletion accurately. The mean statistic of the eight yearly comparisons is 0.86, which indicates a high agreement between actual ET and DSS predicted ET. For six of the yearly comparisons the model efficiency is above 0.94, which is a near perfect agreement. For field 5 in 2009 the value is 0.52 because the field being measured was located in an area where the failure of several weather stations occurred. This resulted in a lower modeled ET than measured. For field 6 in 2009 the value is 0.54 because the field was an old alfalfa field in the last year before reseeding and had a low measured ET. Additionally, the first cut on this field was consumed by geese which further reduced the measured ET. The mean model efficiency for 2008 across both crop types was found to be 0.97 and in 2009 the mean model efficiency for both crop types was 0.80. The variation in modeling efficiency by crop type and year was also examined. Table 5.27 displays the modeling efficiency by year and crop type.

Table 5.27. Nash-Sutcliffe Modeling Efficiency by Year and Crop Type

Crop Type	Year	Mean Model Efficiency
Alfalfa	2008	0.94
Alfalfa	2009	0.76
Grass Hay	2008	0.98
Grass Hay	2009	0.82

From the analysis it appears that the DSS model predicts grass hay ET slightly better than the ET for alfalfa in both 2008 and 2009. The results also indicate that the DSS predictions are more accurate for both crops in 2008 than in 2009.

Overall, the values for the Nash-Sutcliffe modeling efficiency indicate that the DSS predicted ET values will match the measured ET values. A modeling efficiency of 0.86 indicates excellent agreement between the actual measured ET and the DSS predicted ET. The obtained mean modeling efficiency is similar to the Nash-Sutcliffe value of 0.89 that has been found for the SWAT (Soil and Water Assessment Tool) model (Spruill et al. 2000).

In addition to the Nash-Sutcliffe modeling efficiency the seasonal sum for measured ET and DSS modeled ET were also compared. Due to the fact that the sensor set up did not allow for measurements during the period when the soil was draining to field capacity the measurements do not represent a sum of the yearly ET. The difference between the measured values and the DSS was calculated by subtracting the sum of DSS ET from field capacity to irrigation from the sum of the measured ET from field capacity to irrigation across all irrigation events during the season for the eight fields. The absolute error was also calculated for the difference in measured ET sums and DSS predicted ET sums. Table 5.28 displays the values of measured sum ET, DSS sum ET, the difference between the two values, and the absolute error.

Table 5.28: Measured Sum of ET, Sum of DSS ET, Difference, and Absolute Error

Field	Crop	Year	Measured Sum ET from Field Capacity to Irrigation (in)	Sum DSS ET from Field Capacity to Irrigation (in)	Difference (in)	Absolute Error
3	AH	2008	23.5	22.7	0.8	**3.5%**
3	AH	2009	31.9	28.3	3.6	**11.4%**
4	GH	2009	22.1	21.1	0.9	**4.3%**
5	GH	2008	22.5	21.4	1.1	**4.9%**
5	GH	2009	16.5	12.2	4.3	**26.0%**
6	AH	2009	21.6	28.9	-7.3	**34.0%**
8	GH	2008	18.5	20.3	-1.8	**9.9%**
8	GH	2009	16.4	15.7	0.8	**4.8%**

It was found that the mean difference between the measured sum of ET and the DSS predicted sum of ET was 0.3 inches across the eight measurements. The mean absolute difference was found to be 2.6 inches. The mean absolute error across all eight measurements was found to be 12.3%. Work by other researchers suggests that a mean absolute error of 12.3% is an excellent agreement between measured ET values and predicted ET values (Vanclooster and Boesten, 2000; Lascano et al. 1987). In 2008 and 2009 the mean absolute error was found to be 6.1% and 16.1% respectively. This indicates that the DSS predicted the sum of ET more accurately in 2008 than in 2009.

The Nash-Sutcliffe model efficiency values also showed this difference between the two years.

Overall, the mean absolute error of 12.3% indicates that the DSS predicts the sum of ET accurately. The completed analysis using modeling efficiency and mean absolute error indicates that the DSS predicts ET depletion accurately in its current form and can be confidently used to determine ET in the Middle Rio Grande Valley.

The analysis of model formulation indicated that the DSS was capable of creating real time water delivery schedules capable of meeting crop demand. Additional analysis, that consisted of comparing measured crop depletions to DSS modeled crop depletions, indicated that the DSS accurately modeled crop depletions with a mean Nash Sutcliffe modeling efficiency of 0.86. Overall, the validation effort verified the hypothesis that a DSS can be used to develop water delivery schedules based on real time crop demand.

CHAPTER 6 IMPLEMENTING SCHEDULED WATER DELIVERY IN THE MRGCD

This chapter describes the implementation of scheduled water utilizing the developed DSS during the 2009 irrigation season. It describes how the DSS was integrated into the MRGCD SCADA system and explains the training and technical support that was conducted to facilitate scheduled water delivery. This chapter also addresses a public outreach campaign that was conducted to gain support and understanding for scheduled water delivery. The results of scheduled water delivery in the MRGCD during the 2009 irrigation season are also presented. This chapter also describes the benefits that the MRGCD has realized through the use of scheduled water delivery and presents benefits that scheduled water delivery utilizing a DSS could have in other arid regions throughout the world.

6.1 APPROACH

Since the initial conceptualization and formulation of DSS, the overriding goal has been to utilize the DSS to support implementation of scheduled water delivery in the MRGCD service area. During the 2009 irrigation season, water delivery schedules developed using the DSS were implemented in the Peralta Main Canal service area on the East side of the Belen Division. The implementation of the DSS was dependent on a multi-faceted approach that included:

- A complete review of existing MRGCD water delivery policy and practice,
- Gaining support of the MRGCD Governing Board and its administration,
- Training water masters and ditch-riders in the use of DSS model,
- Assisting water masters and ditch riders by running DSS and by developing water delivery schedules,
- Refining parameters in the DSS to address complexities encountered during implementation, and
- Gaining public acceptance for scheduled water delivery.

The following sections describe in detail the overall approach and implementation of scheduled water delivery on the Peralta Main Canal.

Implementation of scheduled water delivery, supported by the DSS, was preceded by careful planning that included intense discussions with the water users, MRGCD field staff and its administration. It was agreed that the implementation be guided by the following considerations:

- Follow a gradual, systematic use and expansion approach,
- Maintain clear communications with the water users, and be flexible so as to address their concerns and needs as much as possible,
- Be consistent with MRGCD water delivery operations policy,
- Obtain MRGCD Board support,
- Let the division level staff implement and manage water delivery operations, assisted by central MRGCD staff and CSU project staff, and

- Provide technical assistance and training to MRGCD field staff to support implementation of scheduled water delivery policy and the use of DSS.

An incremental implementation plan was chosen because it was necessary to address complexities associated with each main canal service area. The incremental implementation plan also allowed for in-depth training and meetings with ditch-riders, which would not have been possible if the DSS had been implemented throughout an entire division of the MRGCD. The gradual implementation also allowed for the dissemination of informational material to water users in a timely manner.

Traditionally, the MRGCD has delivered water to its user's on-demand, with laterals running full continuously. The MRGCD Board, after careful considerations, decided to pursue implementation of its stated policy of scheduled irrigation. The policy states that all water users will receive water based on a schedule, and that water users are responsible for contacting their ditch-riders in advance to schedule water. The revised policy also states that irrigators are required to utilize the water over a 24 hour period each day.

Gaining political support was also an important step in implementing the DSS. Three separate presentations that focused on scheduled water delivery using the DSS were made at the MRGCD Board meetings. These presentations explained the need for water efficiency improvements, and explained how scheduled water delivery using the DSS could decrease diversions and simultaneously provide farmers with water to meet the crop irrigation requirements. The MRGCD Board members were very positive during these meetings and offered their continued support during the implementation process. The overall feeling of the MRGCD Board was that scheduling water in advance was a great idea, and that the DSS would lead to more efficient water delivery, resulting in increased water availability, increased delivery reliability, and equitable distribution among water users.

In order to gain acceptance of the DSS and scheduled water delivery by the MRGCD staff, a significant training and education effort with MRGCD staff was conducted. The training and education effort consisted of individual meetings with ditch-riders and the Belen Division manager and water master. The training of MRGCD staff is described in detail in Section 6.4. The final step in implementing the DSS was to develop schedules at the division level. Decision making at the division level in Belen was crucial to the overall success of the implementation program. In 2009 the DSS was implemented in the Belen Division. The DSS was installed at the central office in Belen and this allowed the Belen Division staff to develop schedules on their own and take ownership of the DSS. Instituting scheduled water delivery at the division level allowed for local refinement and incorporated the expertise and experience of the divisional staff into the development of schedules. Developing schedules at the divisional level was an integral part of implementing scheduled water delivery, and this approach will be continued during expanded use of the DSS in the future.

6.2 DESCRIPTION OF PERALTA MAIN AND METHODOLOGY

In accordance with the gradual approach to implementation, the Belen East area served by the Peralta Main canal was selected for implementation during the 2009 irrigation season. The Peralta Main Canal is highly automated, with modern Langemann gates at most lateral headings that are linked into the MRGCD SCADA system described in Appendix O. This allowed for precise control of water along the entire length of the Peralta Main Canal. The Peralta Main Canal draws water from the Rio Grande on the east side of the Isleta Diversion Dam, and the service area and water delivery operations are managed by four ditch-riders. The farmers in the Peralta Main service area are supplied with irrigation water through a network of 19 lateral and acequia canals that are fed through the Peralta Main Canal. The total irrigated acreage served by the Peralta Main Canal in 2009 was 7,490 acres. Figure 6.1 displays a map of the Peralta Main Canal Service Area with the associated lateral and acequia canals. Table 6.1 presents the canals in the Peralta Main Service area and the irrigated acreage in 2009.

Table 6.1: Canals in Peralta Main Canal Service Area and 2009 Irrigated Acreages

Number	Division Name	Service Area	Irrigated Acreage 2009
1	Belen	Bosque - Smith Lateral	57.6
2	Belen	Braught Lateral	104.0
3	Belen	Chical Lateral	275.6
4	Belen	Chical Lateral Extension	296.1
5	Belen	El Cerro Acequia	173.6
6	Belen	Enrique Lateral	127.6
7	Belen	Hells Canyon Lateral	689.3
8	Belen	Jackson Acequia	147.6
9	Belen	La Costancia Lateral	1084.3
10	Belen	Las Cercas Acequia	327.7
11	Belen	Middle Upper Acequia	280.7
12	Belen	Otero Lateral	1035.8
13	Belen	Peralta Acequia	276.5
14	Belen	Peralta Main Canal	1146.8
15	Belen	San Fernandez # 1 Acequia	67.1
16	Belen	San Fernandez # 3 Acequia	32.9
17	Belen	San Fernandez # 4 Acequia	69.7
18	Belen	Tome Acequia	789.6
19	Belen	Valencia Acequia	306.7
20	Belen	Vallejos Lateral	200.2

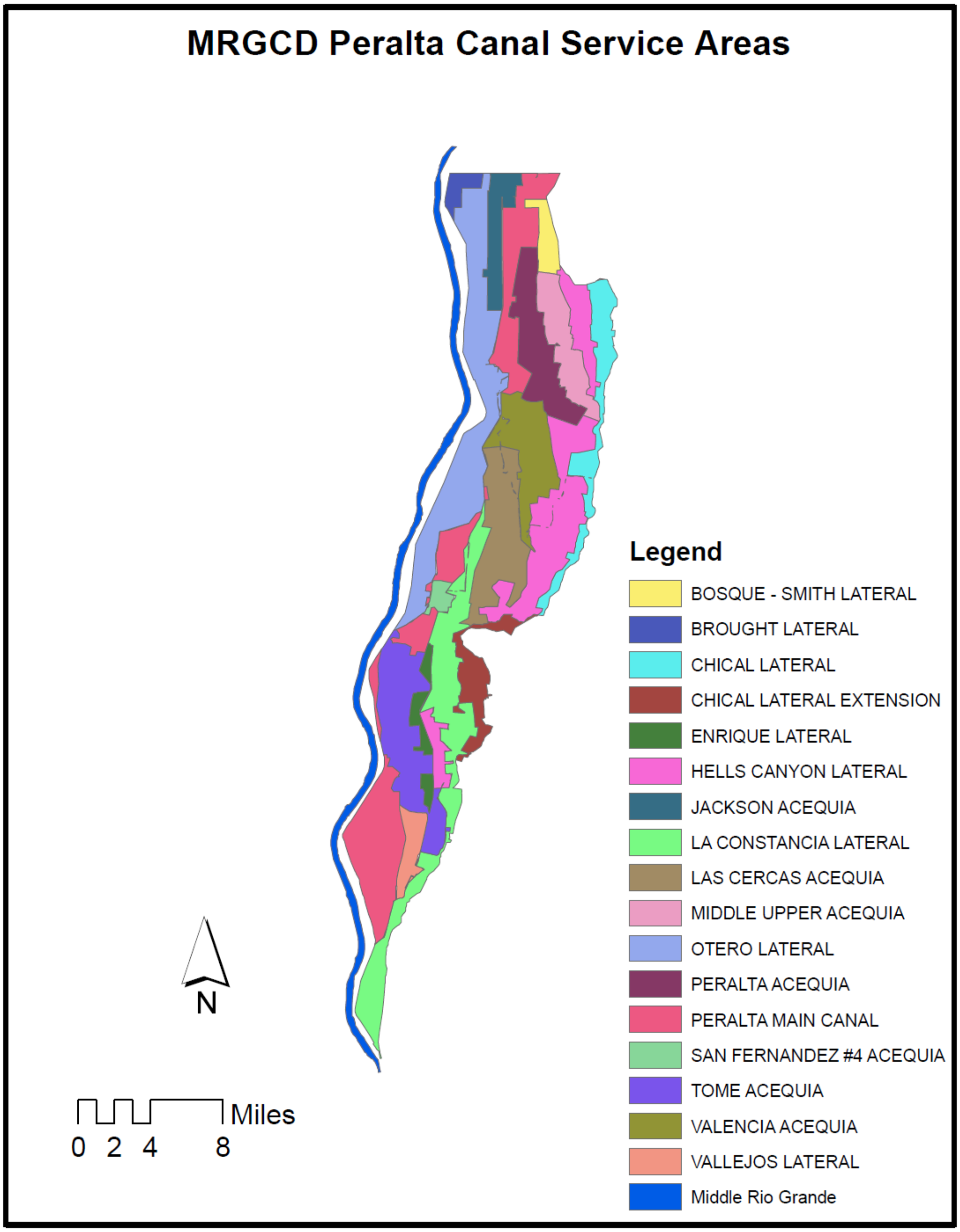


Figure 6.1: Peralta Main Canal Service Area

The first step towards implementation was to inform the water users, especially in the Peralta Main Canal service area. This was accomplished through water user meetings and a public outreach campaign. This was also done by holding a number of small group meetings where key farmers were invited along with the Belen Division ditch-riders. Also a newsletter was prepared and mailed to all water users serviced from the Peralta main canal. The meetings and public outreach campaign is described in detail in Section 6.5. The second step was to intensively train the Belen Division manager and ditch-riders in the use of the DSS model and its utilization in scheduling irrigations for various lateral canal service areas. Through the whole 2009 irrigation season, this researcher assisted the water master and the ditch-riders in using the DSS to generate recommendations in the form of irrigation calendars for each lateral canal on the Peralta Main.

The plan for implementation was presented to the MRGCD Board on October 27th, 2008 and the board granted their support of the plan. A meeting and training session on the DSS was held with all of the Peralta Main Canal ditch-riders, Belen Division manager and water master during the fall of 2008 to familiarize them with the DSS. Prior to the start of the irrigation season, individual meetings with the ditch-riders were held to demonstrate and explain the DSS as well as to answer any questions or address concerns. A final training on using the DSS was held on the Peralta Main Canal at Highway 6. The training and meetings held for implementation of scheduled water delivery and the DSS are explained in detail in Section 6.4.

The first step in the implementation of scheduled water delivery and the development of water delivery calendars was the installation of the DSS on MRGCD operations computers. The DSS for the Peralta Main Canal, with updated acreage and weather data, was installed on the main MRGCD operations computer in Albuquerque, as well as the computer in the Belen Division manager's office to develop water delivery schedules at the division level. Figure 6.2 displays the DSS on the MRGCD water operations computer in Albuquerque.

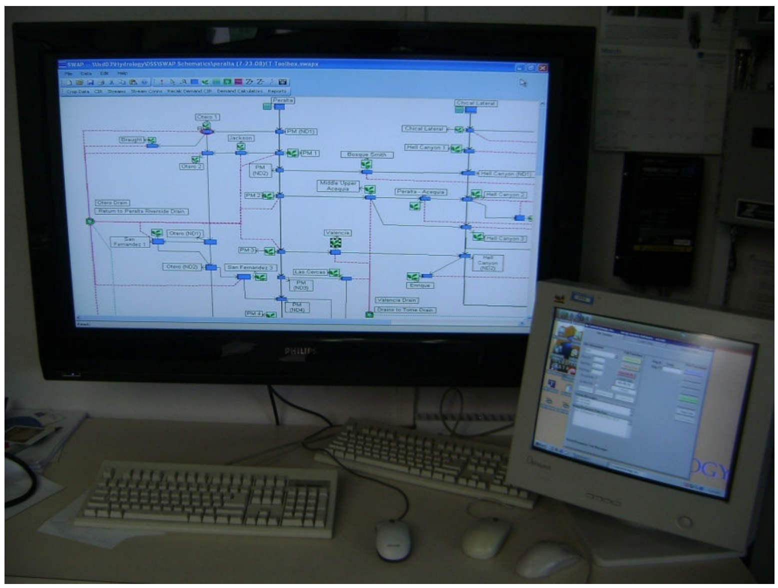


Figure 6.2: DSS on MRGCD Water Operations Computer

Once the DSS was installed on the MRGCD computers, the schematic of the Peralta Main Canal was refined to delineate the four ditch-rider service areas that make up the Peralta Main Canal. The laterals that are in each ditch-riders service area were also aggregated together using the calendar generator in the DSS, so that calendars could be created for each ditch-rider that represented all of the lateral canals in his area. Figure 6.3 displays a section of the DSS schematic that was developed to represent the Peralta Main Canal service area.

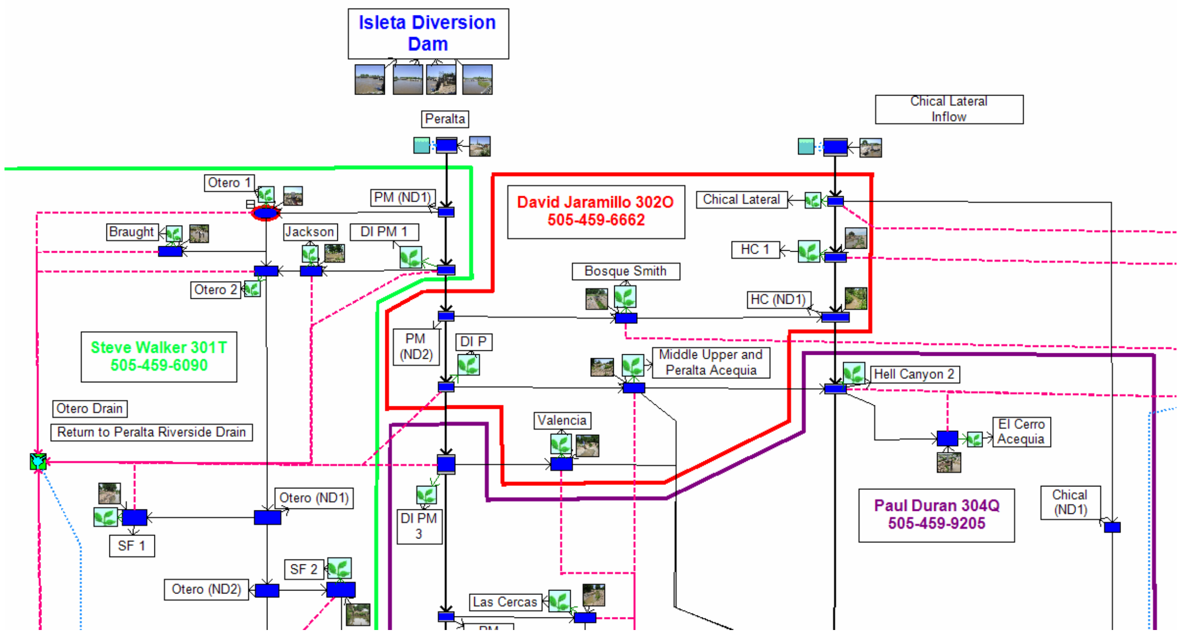


Figure 6.3: DSS Schematic Representing Peralta Main Canal Service Area

Once the DSS was installed on the Belen Division computer, water delivery calendars were generated on a monthly basis. The calendars were generated towards the end of the month so that feedback from the previous month could be incorporated in the next month's schedule. The feedback and data from actual water delivery operations during the previous month were collected from each individual ditch-rider and the Belen Division water master. The feedback and data on actual delivery operations were used to refine the DSS and adjust schedules for the following month accordingly. Figure 6.4 displays a water delivery calendar developed for the Tome Acequia in May of 2009.

Provisional Schedule For Tome For Year 2009
Total Acres 790
Schedule Subject to Change

May

Sun	*Mon*	*Tues*	*Wed*	*Thur*	*Fri*	*Sat*
					1 35 cfs	2 35 cfs
3 35 cfs	4 35 cfs	5 35 cfs	6 35 cfs	7 35 cfs	8 35 cfs	9 35 cfs
10 35 cfs	11 35 cfs	12 35 cfs	13 20 cfs	14 20 cfs	15 10 cfs	16 10 cfs
17 10 cfs	18 10 cfs	19 10 cfs	20 10 cfs	21	22	23
24	25	26 35 cfs	27 35 cfs	28 35 cfs	29 35 cfs	30 35 cfs
31 35 cfs						

Figure 6.4: Water Delivery Calendar Developed for the Tome Acequia in May of 2009

After the water delivery calendars were distributed, daily meetings were held with the Belen Division water master to assess the use of water delivery calendars. Update meetings were also held with the MRGCD water operations manager on a daily basis to inform him of diversion requirements and any changes to the schedule. In addition to the update meetings, this researcher was present on the Peralta Main Canal nearly every day during the irrigation season to assess and provide technical assistance for the water delivery schedules developed using the DSS. The meetings and on the ground support are explained Section 6.4.

6.3 LINKING DSS AND SCADA

One of the key components to implementing scheduled water delivery was linking the DSS water delivery recommendations to the MRGCD SCADA network described in a journal article which can be found in Appendix O. This was done so that water operations personnel could closely monitor the actual canal diversions and compare those diversions to the DSS recommendations on a real-time basis. The overall goal was to match the diversions from the Rio Grande to the real-time crop water requirement calculated using the DSS. The MRGCD SCADA software was used to assist water delivery operations. The software can regulate gate settings to remotely control flow rates and water levels in various water delivery canals. The SCADA Software was developed by Vista Systems and consists of a Graphical User Interface (GUI) that is adapted to represent the canal layouts in MRGCD irrigation system through nodes and links. Currently, there are four GUIs representing the four MRGCD Divisions. Through the canal layouts the user can change the gate settings and flow rates in each canal that is designated in the GUI.

Incorporating the DSS with the MRGCD SCADA system involved three distinct steps. First, the DSS was installed on the MRGCD main water operations computer at the Albuquerque office. Second, the DSS output was converted to a format that the Vista software could recognize. The Vista software uses the SHEF.A. file format for data coming into the SCADA system, and the entire MRGCD canal network is set to function on this format. The data for each individual gate or measuring site are characterized by a distinct data stream in the Vista Software, the data and are linked to the appropriate node in the SCADA GUI. The data stream for each node in the GUI is user specified; and therefore, nodes were created that display DSS recommended flow rates. In order to link the DSS to this SCADA software it was necessary to create DSS output files in SHEF.A. format. This was accomplished through cooperative work between Colorado State University, the MRGCD, and Vista Systems. During a meeting in Los Alamos at Vista Systems, the programmers were able to write a subroutine in the MRGCD SCADA Vsystem software that converts the output from the DSS into the SHEF.A. format. This subroutine allows for the creation of separate data streams from the DSS schedule for each lateral canal service area. These data streams are the same data streams that are used throughout the MRGCD SCADA network.

The third step in linking the DSS was to create a node for the DSS recommended flowrate for each lateral service area in the SCADA GUI that also contains actual flowrate data. This consisted of creating nodes in the SCADA GUI that display the actual flow passing into a lateral on the left side of the node and the recommended flowrate from the DSS in parentheses. The DSS recommended flow was linked to the correct data stream from the DSS output in SHEF.A format. For the 2009 irrigation season actual flow and the DSS recommended flow were displayed side by side for each lateral on the Peralta Main Canal in the SCADA GUI. Figure 6.5 displays the revised SCADA GUI with the DSS recommendations.

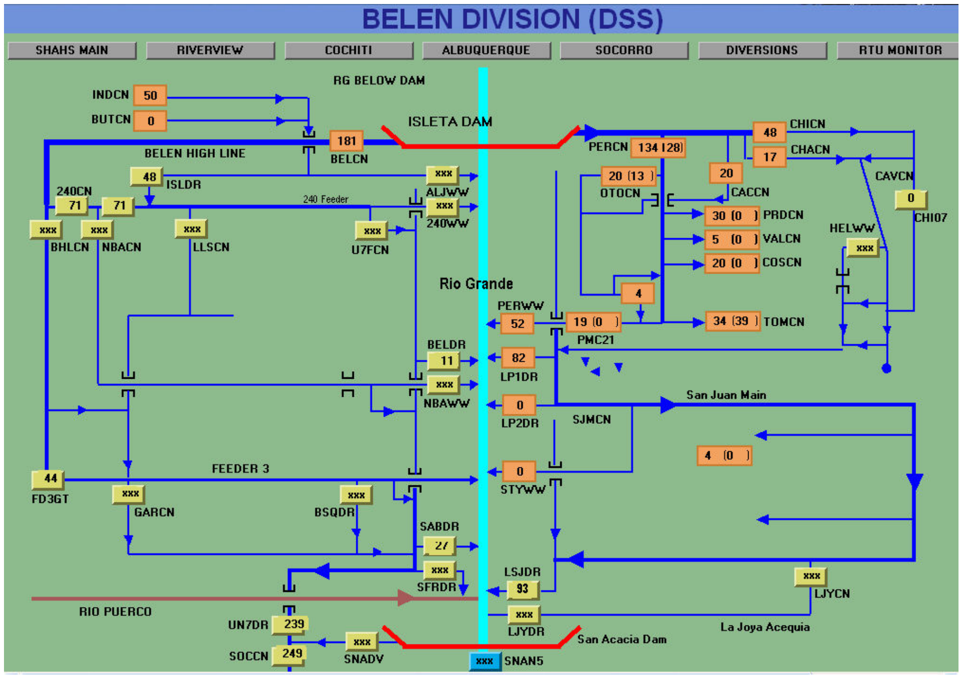


Figure 6.5: MRGCD SCADA Screen with Actual Deliveries and DSS Recommendations

To update the recommendations for the DSS flowrates, the DSS was run and the scheduler output was saved as a CSV file in Excel. This file was then converted using the Vsystems subroutine and was available as a SHEF.A. data stream for each individual lateral. Linking the DSS water distribution recommendations with the MRGCD SCADA provided a simple and effective medium for managers to implement DSS water delivery schedule. Additionally, the combination of both programs allowed for real-time management that allowed for the convergence of river diversions and the water required based on crop demand.

6.4 TRAINING OF MRGCD STAFF AND TECHNICAL ASSISTANCE

Training of MRGCD staff and providing technical assistance of the DSS proved to be a crucial element in the implementation of scheduled water delivery on the Peralta Main Canal. The training familiarized the MRGCD staff with the use of the DSS and water delivery calendars and it also provided on the ground support necessary to answer questions, resolve conflicts, and make refinements to the DSS.

Preliminary training of the ditch-riders on the Peralta Main Canal was conducted during the fall of the 2008 irrigation season. The preliminary training consisted of briefly explaining the DSS and providing ditch-riders with example water delivery schedules. The plan of implementing scheduled water delivery during the following irrigation season, 2009, for the entire Peralta Main Canal was laid out, and ditch-riders were made aware that they would receive monthly water delivery calendars of when their ditches would be scheduled on or off. The principle that the schedule would be based on crop demand and equitably distribute water between the ditch-riders was also explained.

6.4.1 Utilizing DSS for Scheduling Recommendations

Prior to the start of the 2009 irrigation seasons, a meeting was held in the Belen Division main office with all of the ditch-riders on the Peralta Main Canal, the Belen Division manager, and the Belen water master. During this meeting the plan for implementing scheduled water delivery using calendars developed through the DSS was reiterated and the Division Manager made clear to the ditch-riders that they were to follow the water delivery calendars to the best of their abilities. The Belen Division manager and project staff also identified the need for the ditch-riders to be proactive in contacting water users and informing them in advance as to what days the water would be available for irrigation on a lateral. This point was crucial in the implementation of the DSS, as water users would want water off the schedule if they were not adequately informed. The fact that many water users traditionally do not irrigate at night was also addressed during this meeting.

The Belen Division manager and water master made clear to the ditch-riders that the water delivery calendars were based on 24 hour irrigation and they would be required to schedule the use of water at night. The MRGCD policy states that water users are to irrigate 24 hours a day when water is being scheduled, and this meeting was used to remind the ditch-riders about this policy. The meeting ended with the Belen Division manager stating that scheduling water deliveries was the new policy for the Peralta Main Canal and that eventually the entire Belen Division would be using calendars to schedule water delivery. The Belen Division manager finished the meeting by telling the ditch-riders that he expected them to follow the schedules as closely as possible, record their daily canal operations, and contact project personnel when the schedules could not be followed.

To follow up the initial discussions, regular meetings were held with each individual ditch-rider to explain the DSS in detail. This included a demonstration of the DSS and its use on a lap-top in the field. During these meetings the ditch-riders were shown the ditches in their service areas on the DSS GUI. This included showing each ditch-rider the irrigated acreage and crop type, as well as the soil characteristics for each of their laterals. The ditch-riders were also shown how the weather data are imported into the DSS and how it is used to calculate the consumptive irrigation requirement. They were also shown how the water delivery calendars are created, and were educated about the basic principles used to develop the calendars. Using the DSS on an entire main canal to provide equitable and organized water delivery amongst ditch-riders was also explained. These meetings with individual ditch-riders to demonstrate the DSS provided the training necessary for ditch-riders to correctly explain the DSS and scheduled water delivery to water users.

The final training of MRGCD staff occurred a week before the start of the irrigation season. This training was conducted at the junction of Highway 6 and the Peralta Main Canal, with all ditch-riders for the Belen Division present, as well as the division manager and water master. The training began with an overview of the DSS concepts and the data being used to calculate the water delivery schedules, such as weather data, crop type, acreage, soil types, and canal capacities. During this training the ditch-riders were provided with water delivery calendars for the month of March and shown how to use them. The idea of contacting water users in advance and notifying them when water was going to be available based on the schedule was reiterated. The Belen Division manager informed the ditch-riders that scheduling water delivery was the MRGCD policy and reinforced that the schedules were to be adhered to as much as possible. The ditch-riders were also provided with a central phone number to contact this researcher with any questions, concerns, or problems related to the DSS schedules. During this meeting the ditch-riders were also trained in the use of Aquaterr soil moisture testers. Prior to the start of the irrigation season, the MRGCD purchased five Aquaterr soil moisture meters to be used on the Peralta Main Canal. The probes were purchased so that ditch-riders could determine if irrigation was warranted on a specific field and to continuously check soil moisture levels in their areas. Another purpose of using the Aquaterr meters was to educate farmers about their irrigation practices. The Aquaterr is a portable conductance probe that determines soil moisture levels across various soil types. During the meeting the ditch-riders were shown how to calibrate the Aquaterr probe and how to use it to determine the average soil moisture content in a field. Figure 6.6 displays training in the use of DSS water delivery calendars and Figure 6.7 displays training on using the Aquaterr soil moisture meter.

Figure 6.6: Training MRGCD Staff to Use DSS Scheduling Calendars

Figure 6.7: Training MRGCD Staff to Use the Aquaterr Soil Moisture Meter

Overall the training of ditch-riders on the use of water delivery schedules and the Aquaterr meter was positive. The ditch-riders were especially pleased with the Aquaterr soil moisture probe, as it gave them an on the ground check whether a field indeed needs to be irrigated or has sufficient soil moisture. Water delivery calendars were also distributed to ditch-riders on a monthly basis during the 2009 irrigation season, and a follow up meeting was held with each ditch-rider every month to gain feedback from the previous month. During these meetings, the ditch-riders explained how well they were able to follow the water delivery schedules and what obstacles they faced in holding to the schedules. This feedback was crucial for refining the DSS for future water delivery calendars.

Training on the use of the DSS was also carried out with the MRGCD hydrologists, the Belen Division manager, and the Belen water master. This was conducted at the end of the 2008 irrigation season and repeated at the beginning of the 2009 season. The training was conducted both in the Albuquerque and Belen main division offices. The MRGCD staff was instructed on how to install the DSS, and the DSS was installed on the MRGCD main water operations computer in Albuquerque and a computer in the Belen Division office. The MRGCD staff was also trained to upload and update databases, and how to create water delivery schedules. Copies of the DSS program, schematics, and databases were supplied to the Belen Division water master and division manager during the fall of 2008 so that they could run the DSS from home during the winter and become familiar with the program. During this time technical assistance was provided by telephone when questions regarding the use of the DSS arose. This was done so that the water master and division manager could become familiar with the DSS prior to the irrigation season. The training of MRGCD staff prior to the 2009 irrigation season involved going over the use of the DSS and assisting the staff in running the DSS on their own.

6.4.2 On Site Support

During the 2009 irrigation season on the ground technical assistance was provided for implementation of the water delivery schedules on the Peralta Main Canal. The technical assistance consisted of aiding the MRGCD in the development and distribution of water delivery calendars using the DSS. Before schedules were generated the newest version of the DSS was installed on the computer in the Belen Division and the databases for the DSS were updated to reflect the current weather conditions. Water delivery calendars were created every month for the laterals on the Peralta Main Canal and distributed to the Belen Division water masters, ditch-riders, and MRGCD hydrologists. At the end of each month this researcher aided the MRGCD by collecting notes from the ditch-riders on actual water delivery during the previous month, as well as any comments or feedbacks that were used to refine the DSS.

Technical assistance also consisted of checking on water operations on the Peralta Main Canal on a daily basis. Every morning a phone meeting was held between the Belen Division water master and this researcher to access the daily water delivery schedules. During this daily meeting the total water delivery for the Peralta Main Canal was discussed, as well as how well the ditch-riders were able to follow the DSS recommendations for the day ahead. The water master conveyed any changes that had to be made to the schedules to the project staff and explained why changes were needed. During these meetings the current farming practices were also discussed, such as when farmers were going to be cutting and bailing, which allowed schedules to be adjusted accordingly. Canal maintenance and other operational procedures that would affect water delivery were also discussed, and recommendations to overcome these changes were provided by this researcher. Technical questions related to the use of the DSS were answered during these meetings. In addition to the phone meetings this researcher was present on the Peralta Main Canal nearly every day to assess and document water delivery scheduling.

Daily meetings to update the MRGCD water operations manager were held with this researcher at the Albuquerque Main Office. These meetings served to update the water operations manager of any changes to the DSS schedules and to inform him of required water deliveries for the following several days. This information was used to coordinate dam releases during the second half of the irrigation season. The meetings were also used to judge the performance of the DSS schedules and the ability of the water master and ditch-riders to stick to the schedules. During these meetings the real-time flow for the canals on the Peralta Main Canal were checked using the MRGCD SCADA system. Using the MRGCD SCADA network the water delivery practices for each automated canal on the Peralta Main were periodically downloaded for direct comparison to the DSS water delivery schedules. The daily meetings with the water operations manager proved vital to the implementation of the DSS, because daily changes could be made and monitored, and progress could be assessed on a real-time basis.

6.4.3 Obstacles During Field Implementation and Response

During the implementation, several obstacles to scheduled water delivery were discovered. The following section describes the obstacles that were able to be addressed through refinement of the DSS and other obstacles that could not be addressed. For several laterals the time to irrigation value in the DSS represented a value that was too short to supply adequate water to all irrigators. This discrepancy arose as many irrigators have fields that take a significant amount of time to irrigate due to small turnouts, low check structures, and lack of laser leveling on the fields. During the 2009 season the time to irrigation for each lateral on the Peralta Main canal was adjusted, based on ditch-rider feedback and on the ground observation, to reflect the actual time required for an entire lateral to be irrigated.

The second refinement to the DSS consisted of adjusting the canal capacity for each lateral on the Peralta Main Canal. This was done because several of the ditch-riders did not utilize the full capacity of the lateral due to operational constraints. The operational constraints consisted of road crossings and culverts that did not allow the ditch-rider to run a lateral at maximum capacity. In these cases the flow rates in the DSS were reduced to reflect the operational practices of the ditch-riders. In other cases the flow rate represented in the DSS was too low. When the flow rate was too low the value in the DSS was changed to reflect the actual carrying capacity of the canal.

The third major obstacle that was dealt with during the refinement of the DSS was the routing of supply water to the Hell Canyon Lateral. Due to the nature of the Peralta Main Canal layout, the Bosque Smith Acequia and the Peralta Acequia are used to route water to the Hell Canyon Lateral when Isleta Pueblo irrigators are utilizing water. To account for this supply water a constant flow of 20 cfs was added to the water demand of the Bosque Smith Acequia.

The final refinement made to the DSS during the 2009 season was the aggregation of the Peralta Acequia and the Middle Upper Acequia. In the original Peralta schematic the Peralta Acequia and Middle Upper Acequia were represented by two demand nodes. During the implementation it was determined that the ditch-rider operated these acequias as essentially one canal since both ditches share the same heading on the Peralta Main Canal. Providing two separate schedules for these ditches proved cumbersome and did not represent the ditch-rider operational practices. To alleviate this, demand areas were aggregated and the ditch-rider received a schedule that combined both of the acequias. This aggregation was a useful refinement as it accurately represented operational practices.

During the implementation several obstacles were identified that could not be addressed by DSS refinement and these included:

- Farming practices such as cutting, bailing, and fertilizer application
- The planting of new fields in the spring and fall
- Pueblo irrigators utilizing upstream water
- Farmers not being able to utilize water when it was available

Farming practices could not be addressed through the refinement of the DSS, because the DSS does not account for cutting, bailing, and fertilization cycles on an individual farm level. The variability in farm practices resulted in situations where water was not available in a lateral when farmers wanted to irrigate. When these situations occurred, water was made available by the water master to accommodate the farmers that could not stick to the schedule due to cutting and bailing cycles.

The planting of new fields also presented a situation that could not be directly accommodated by the DSS. The planting of new fields requires water roughly every seven days for the seeds to germinate and establish a root zone. At the beginning of the irrigation season planting was prevalent, as well as during the middle of the season when farmers were planting corn. The situation arose again at the end of the season when farmers were planting fields for the spring. To address this situation a lower flow rate was left in acequias by the water master during times that the ditch was scheduled to be off. This allowed farmers with new crops to irrigate with reduced water.

The irrigation practices of Isleta Pueblo was another problem that refinements to the DSS could not address. The Isleta Pueblo irrigates lands off the Peralta Main Canal north of the MRGCD lands. When the Pueblo irrigated, the flow in the Peralta Main canal would drop and the required flow to satisfy the DSS calendars was not available downstream. When this occurred the water master placed extra water in the Peralta Main Canal to make up for the water that the Pueblo was utilizing. Another issue related to Pueblo irrigation was the control of canal head gates. The headings of the Chical Lateral, Hell Canyon Lateral, and Otero Lateral are located on Isleta Pueblo and are controlled by pueblo irrigators. Since the MRGCD does not have control of these head gates, it was not possible to fully implement the water delivery schedules on these canals.

The last major obstacle that was encountered during the implementation was that farmers did not always utilize the water when it was available. Several farmers on the Peralta Main canal insisted that they could only irrigate on certain days of the week or could not irrigate at night. When this occurred the ditch-riders would meet with the farmers to explain to them that they were required to make use of the water when it was available and that schedules were based off crop demand and would not fall on regular days. The ditch-riders did their best to accommodate theses farmers, and when a distinct need for water was determined, a reduced flow rate was used to provide water to the farmers in question.

6.5 PUBLIC OUTREACH

In order to realize scheduled water delivery utilizing the DSS in the MRGCD in 2009 it was necessary to gain acceptance and adoption from water users. However, to gain acceptance and adoption it was important for water users to fully understand the practice of scheduled water delivery and the DSS. To achieve the goal of informing water users about scheduled water delivery and the DSS, a public outreach program was developed and carried out. The public outreach program was focused on providing water users with information regarding the need to practice scheduled water delivery that is based on crop water requirements, and how scheduled water delivery can be implemented through the use of the developed DSS. In addition to educating farmers about scheduled water delivery and the DSS, the public outreach program also solicited comments and suggestions from water users. The key components of the public outreach program were disseminating information to water users and holding meetings with the water users to explain schedule water delivery and the DSS.

6.5.1 Dissemination of Information

In order to disseminate the information regarding the DSS, scheduled water delivery and its implementation, it was necessary to reach as many water users as possible. To ensure that the information reached a wide audience, it was made available to water users in multiple forms. The forms of information included the MRGCD website, the MRGCD newsletter, and a dedicated flyer to all water users in the Peralta Main canal service area in 2009. The overall goal was to try and reach each water user in the MRGCD with at least one form of information describing the DSS and scheduled water delivery.

6.5.1.1 MRGCD Website

The first step in disseminating information was to provide an article that describes the DSS and how it is used to develop water delivery schedules on the MRGCD website, www.mrgcd.com. Figure 6.8 displays the link to the article on the MRGCD homepage and Figure 6.9 displays the article about the DSS.

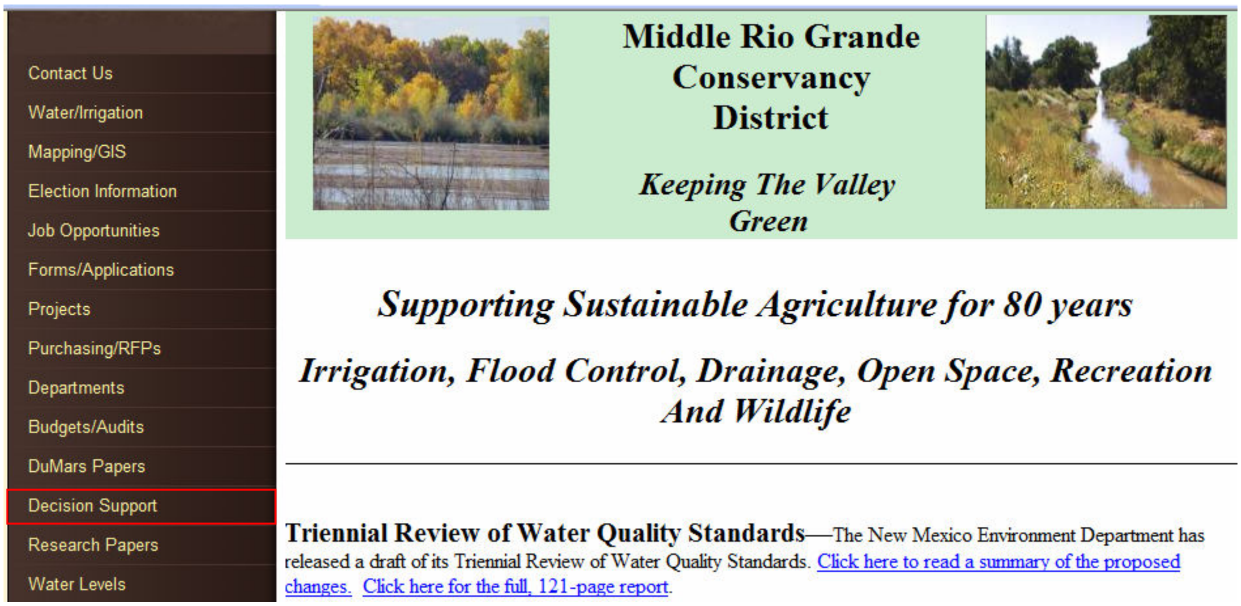


Figure 6.8: MRGCD Homepage Displaying DSS Link to DSS Information

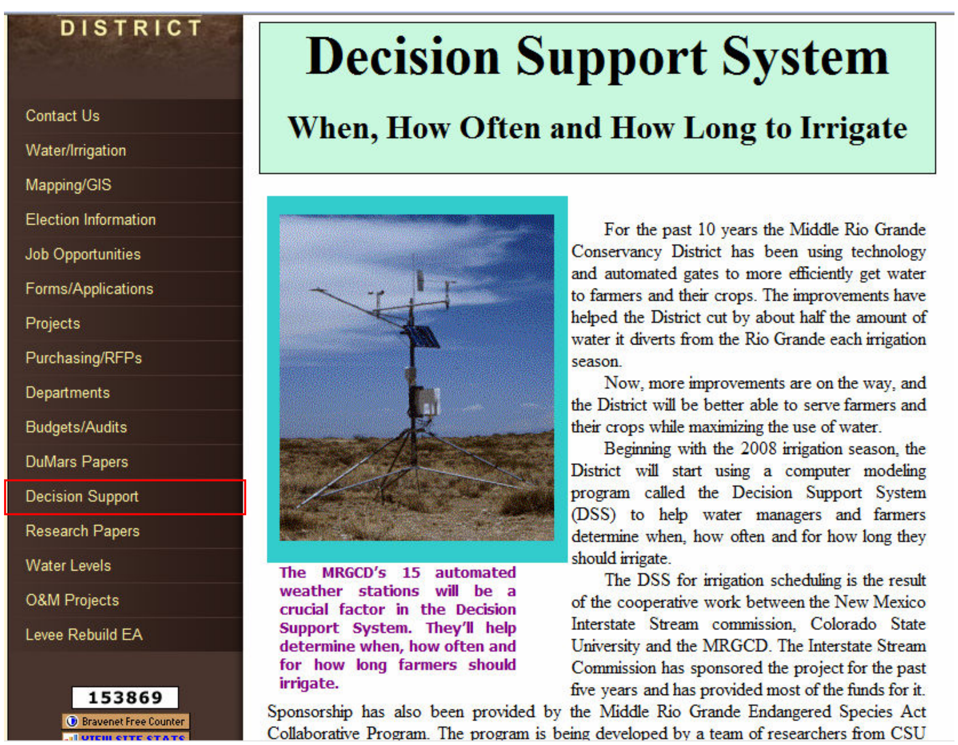


Figure 6.9: Article Explaining DSS on MRGCD Website

The DSS project reports from 2007, 2008, and 2009 were also linked to the MRGCD website to provide information about the DSS and scheduled water delivery. Additionally, three research papers related to the DSS, scheduled water delivery, and irrigation system modernization (Gensler et al. 2009, Oad et al. 2009, and Oad and Kullman, 2006), were made available on the MRGCD website under the research papers link. These three papers and two additional papers related to soil moisture sensors and canal seepage are included in the Appendix.

6.5.1.2 Newsletters and Flyers

To provide information regarding the DSS through already established information networks, the quarterly MRGCD Newsletter was used to distribute an article explaining the DSS and scheduled water delivery. In all, about 50,000 water users, property owners, and other stakeholders in the Middle Rio Grande Valley received the MRGCD Newsletter. The article titled "Computer Irrigation Scheduling Software to Remove Guesswork for Irrigators" briefly explained why it is necessary to schedule irrigation in relation to crop water demand and how the practice can result in more efficient and productive use of irrigation water. The MRGCD article is included as Appendix P. The article was also posted on the MRGCD website, and is linked to other related information such as crop water requirements and better on-farm water management practices.

To facilitate implementation of DSS water delivery schedules on the Peralta Main Canal, during the 2009 irrigation season, a dedicated flyer was composed and mailed to 1223 water users on the Peralta Main Canal. The flyer described the need for scheduled water delivery, the use of the DSS to develop water delivery calendars, and the support of the MRGCD Board in implementing scheduled deliveries. The flyer also included a schematic representing the DSS structure and an example calendar of water delivery on a lateral. The flyer also included contact information of project personnel to address any questions or concerns from water users regarding the implementation of the DSS and scheduled water delivery. The flyer is included as Appendix Q.

6.5.2 Water Users Meetings

A key component of the public outreach and information program was holding water users meetings. In previous years water users meetings were held in the Albuquerque, Belen and Socorro Divisions. These water users meetings provided a venue to explain the DSS and the scheduled water delivery concept. These water users meetings also provided water users with an opportunity to voice questions and concerns, and provide vital feedback to the MRGCD. The previous public outreach meetings proved to be important in the implementation of the DSS on the Peralta Main Canal because many of the large water users attended these previous meetings. Figure 6.10 displays a public outreach meeting held in the MRGCD.

Figure 6.10: Public Outreach Meeting

To continue the public outreach meetings during the implementation of the DSS on the Peralta Main Canal in the Belen Division, a meeting was held in the Belen Division office at the start of the irrigation season (February 25, 2009). The attendance at the meeting consisted of major water users, the chairman of the MRGCD Board, the Belen Division manager and water master, and the MRGCD water operations manager. During this meeting a presentation was made explaining the concepts behind the DSS and the plans for implementation of scheduled water delivery on the Peralta Main Canal during the 2009 irrigation season. Questions and concerns from the water users were also addressed. This meeting proved to be quite productive and several suggestions during the meeting were incorporated in the implementation of the DSS. The major suggestion incorporated during the meeting was that water delivery schedules should be developed at the Belen Division main office so that the division office can take ownership of the DSS and operate it at a local level to address local conditions on the ground.

In addition to the meeting held in the Belen Division office at the start of the season, meetings with individual farmers were held throughout the Peralta Main Canal service area during the irrigation season (April 22, 2009). Farmers voiced their questions and concerns with their ditch-riders. These farmers were identified by the ditch-riders and meetings were set up between the farmer, ditch-rider and this researcher at the farmer's field. During these meetings the DSS and scheduled water delivery were explained in detail and fears regarding the availability of water were assuaged. The main concern that farmers had was that farmers would be short-changed by decreasing the river diversion. Explaining the DSS and that water delivery using the DSS is based on the water requirements of crops reassured the water users and addressed most of their concerns.

In addition to the meetings with individual farmers, a cell phone number was made available for the ditch-riders to distribute to farmers with questions or concerns. When farmers called, this researcher explained the DSS and held conversations to address the questions from water users. Through the meetings with individual farmers and phone conversations, over 100 farmers were contacted, which represents 10% of the farmers on the Peralta Main Canal. The practice of having a central person that could readily be contacted was crucial to the implementation of the DSS and should be continued for the future expansion of scheduled water delivery.

During the 2009 irrigation season, the MRGCD Board opted to hold meetings in the Belen and Socorro Divisions so that more water users could attend the meetings.

These meetings were well attended with nearly 100 water users present at the Belen meeting (April 27, 2009) and over 40 water users attending the Socorro meeting (July 27, 2009). At each of these meetings questions about the DSS and scheduled water delivery arose and CSU researchers, water masters, division managers and the MRGCD water operations manager were present to answer questions. Attending these meetings provided another venue to distribute information and talk directly with water users. During both of these meetings the MRGCD Board offered their continued support of scheduled water delivery using the DSS, which reinforced the idea with water users. Table 6.2 displays a list of the major meetings that were held with water user groups during the 2009 irrigation season.

Table 6.2: Meetings Held with Water Users during the 2009 Irrigation Season

Meeting Location	Date
Belen Division Office	2/25/2009
Peralta Main Canal and HWY 6	2/26/2009
Isleta Dam	3/9/2009
MRGCD General Office	3/12/2009
Tome Acequia	3/18/2009
240 Wasteway	3/24/2009
Dos Locos Loop	3/26/2009
Belen Division Office	3/29/2009
Belen Division Office	4/22/2009
Belen Public Library	4/27/2009
South Bosque Loop	5/25/2009
Otero Lateral	6/26/2009
Enrique Acequia	7/9/2009
MRGCD General Office	7/21/2009
Isleta Dam	7/27/2009
Board Meeting Socorro	7/27/2009
Candelaria Farm	8/27/2009

Overall, the public outreach effort was effective and successful. The meetings with water users in the Belen Division, both on farms or through phone conversations, were especially productive, and established a personal relationship between the water users and CSU researchers. The MRGCD Board meetings in Belen and Socorro provided an additional venue for the MRGCD water users to learnthe MRGCD's future plans related to water delivery operations, as well as to ask questions, and provide valuable suggestions. These inputs from water users provided critical information for the DSS implementation and for irrigation water scheduling.

6.6 RESULTS OF SCHEDULED WATER DELIVERY

The overall results of implementing scheduled water delivery utilizing the DSS have been overwhelmingly positive. Throughout the 2009 irrigation season the ditch-riders were able to follow the recommended water delivery schedules, and as a result, water distribution was improved. The water operations manager, Belen Division manager, water master, and ditch-riders believe the DSS assisted in scheduling and streamlining water delivery operations. Since automated Langemann gates were installed on 6 of the 20 canals in the Peralta Main service area, it was possible to compare the actual water deliveries to the deliveries suggested by the DSS. The comparison of the diversion on the Peralta Main Canal, Peralta Acequia, La Constancia Acequia, Otero Lateral, Tome Acequia and Valencia Acequia are presented in Sections 6.6.3 through 6.6.8.

6.6.1 MRGCD Water Operations Manager

From the stand point of the water operations manager, the DSS provides a very useful tool for the MRGCD to manage water. The DSS brings hard numbers and a logical analysis process to what has traditionally been an imprecise and subjective decision making process in regards to water delivery. The DSS allows the water operations manager to estimate demands and operate the system in a more stable and predictable manner than previously possible. Using the DSS, water is scheduled for delivery at a certain time and the system becomes more stable and water deliveries to irrigators have become more reliable. The DSS has been extremely helpful for the water operations manager because it gives him a rationale for water delivery. It allows him to plan deliveries in advance and there is a reason behind the amount of water. The DSS has a justification (Crop Demand) for diversions where in previous year's water usage was a simple guess or a desired flow from the ditch-rider.

Knowledge of water demand in advance also allows the water operations manager to release stored water in a timely manner to ensure it is available to meet crop demand downstream. The DSS also has the benefit of getting the ditch-rider to schedule irrigators in blocks when water is there. Finally, the DSS also provides a large quantity of information for the water operations manager that is easily accessible. This includes the physical layout of canals, capacities, leakage rates, routing, cropping patterns, and soil types and this information can be easily referenced and used to make water delivery decisions. The water operations manager regularly uses the DSS to check acreages and the amount of water being delivered to laterals on his operations computer.

6.6.2 Belen Division Manager and Water Master

The Belen Division Manager believes that the DSS is a great tool that provides the organization that has been lacking in water delivery. Having water delivery schedules in advance facilitates coordination between the ditch-riders and provides oversight for the water master. The schedules developed using the DSS also lead to better coordination between the farmers and ditch-riders because the ditch-riders are forced to call farmers and notify them when water is going to be available. The training provided during the implementation of the DSS was also helpful because it provided the ditch-riders with the knowledge to explain the DSS in depth and address water users concerns

The Belen Division water master is satisfied with the DSS and water delivery scheduling and believes it is the best method for coordinating water delivery that he was utilized in his nine years with the MRGCD. The fact that the schedules are calculated using crop demand provides each ditch-rider with a block of water to satisfy the crop needs in his area. The flow targets from the DSS also give the water master hard numbers to work with, which eliminates the guesswork of previous years. The structure of the DSS also ensures that the water is fairly and equitable distributed amongst the ditch-riders. He believes that scheduled water delivery using the DSS is the most efficient method of delivering water and that the DSS provides the organization necessary for optimum water management. Through the implementation of the DSS the water master has observed that ditch-riders are able to schedule water seven to ten days ahead of time, which was unheard of in previous years. The schedules have also forced the ditch-riders to schedule farmers in groups which results in less water returning to drains.

The four ditch-riders on the Peralta Main Canal have found the DSS schedules to be helpful in their daily water delivery operations. The ditch-riders have been able to consistently follow the recommended schedules and feel that the DSS provides organization between them in an equitable manner. The ditch-riders have found that shutting off the ditches for a period of time ensures that farmers will need water. This has aided the ditch-riders in organizing water delivery on each ditch and lining up farmers to efficiently use the available water. The ditch-riders have also found that through the use of the water delivery schedules farmers have been more compliant about calling for water in advance. Throughout the season the farmers received their water allocations and complaints about equitable water distribution have been significantly less than in previous years

6.6.3 Peralta Main Canal Diversion

Through the use of the installed Langemann gate at the heading and SCADA telemetry it was possible to record the flow rate being delivered to the Peralta Main Canal every thirty minutes during the 2009 irrigation season. These values were compared to the flow rate values suggested by the DSS water delivery calendars to access how well the ditch-riders and water masters were able to follow the DSS recommendations.

The first comparison that was analyzed for the Peralta Main Canal diversion was the daily value of flow rate in cubic feet per second. The daily flow rate values showed significant variability although the DSS and actual diversion numbers showed the same general trend. Figure 6.11 displays the daily flow rate suggested by the DSS and the actual flow rate for 2009.

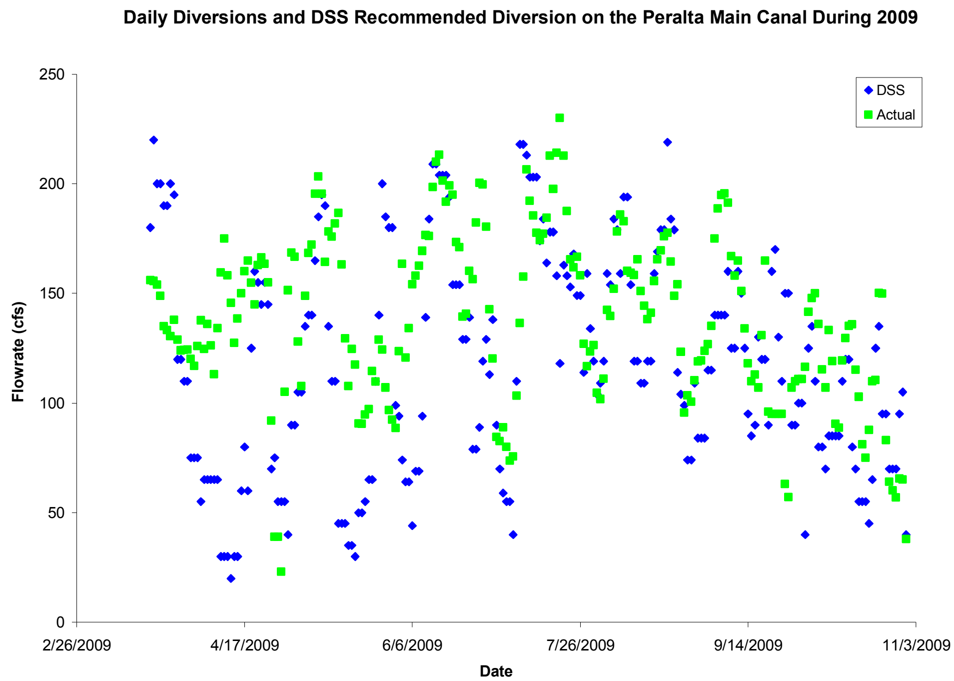


Figure 6.11: DSS Daily Flow Rate and Actual Flow Rate for Peralta Main Canal in 2009.

To analyze the variability in the daily flow rate values for the Peralta Main Canal the Nash Sutcliffe modeling efficiency statistic was calculated. This statistic has been utilized extensively for assessing predictive flow models and evapotranspiration and is explained in detail in Section 5.3.2. The Nash Sutcliffe value for the fit between the modeled DSS daily flow rate and the actual daily flow rate was found to be -0.63. This indicates that on a daily basis the DSS modeled flow did not represent the actual practice sufficiently. There are many reasons for this and they include farming practices such as cutting and bailing, the planting of new fields, pueblo irrigators utilizing water without advance notice, and farmers not utilizing water when it was available. These reasons are discussed in detail in Section 6.4.3.

Since the Nash Sutcliffe value indicated that the DSS daily flow rate and actual daily flow rate utilized on the Peralta Main Canal during 2009 showed significant variability it was deemed appropriate to analyze the monthly, yearly and cumulative daily diversions to eliminate the variability. This was deemed appropriate as the DSS creates schedules that call for irrigation water approximately every two weeks.

The actual monthly diversion values and the DSS predicted values were calculated in acre feet. For the Peralta Main Canal both the actual diversion and DSS suggested monthly diversions showed a bell curve shape characteristic of a canal that is used to supply water for crop demand. The actual diversion numbers on a monthly basis were higher than the DSS suggested value in every month except March. The reason for this was that the soil moisture level at the start of the irrigation season was set to 0% RAM remaining which resulted in the model suggesting a high diversion to fill the deficit in soil moisture at the start of the season. Based on the actual diversions it appears that this assumption was conservative as the actual diversion was 859 acre feet lower than the DSS suggested diversion in March. From the analysis completed in Section 5.1.5 a value of 10% RAM remaining would have been more appropriate. The three months of April, May, and June towards the beginning of the season showed the largest difference between the DSS recommendations and actual diversions. During the later half of the season the difference between the actual diversions and the DSS recommendation decreased. The most plausible reason for this difference is that the ditch-riders and water master on the Peralta Main Canal became more comfortable and adept at implementing the water delivery schedules suggested by the DSS. Figure 6.12 displays the comparison between the actual monthly diversion and the DSS suggested diversion.

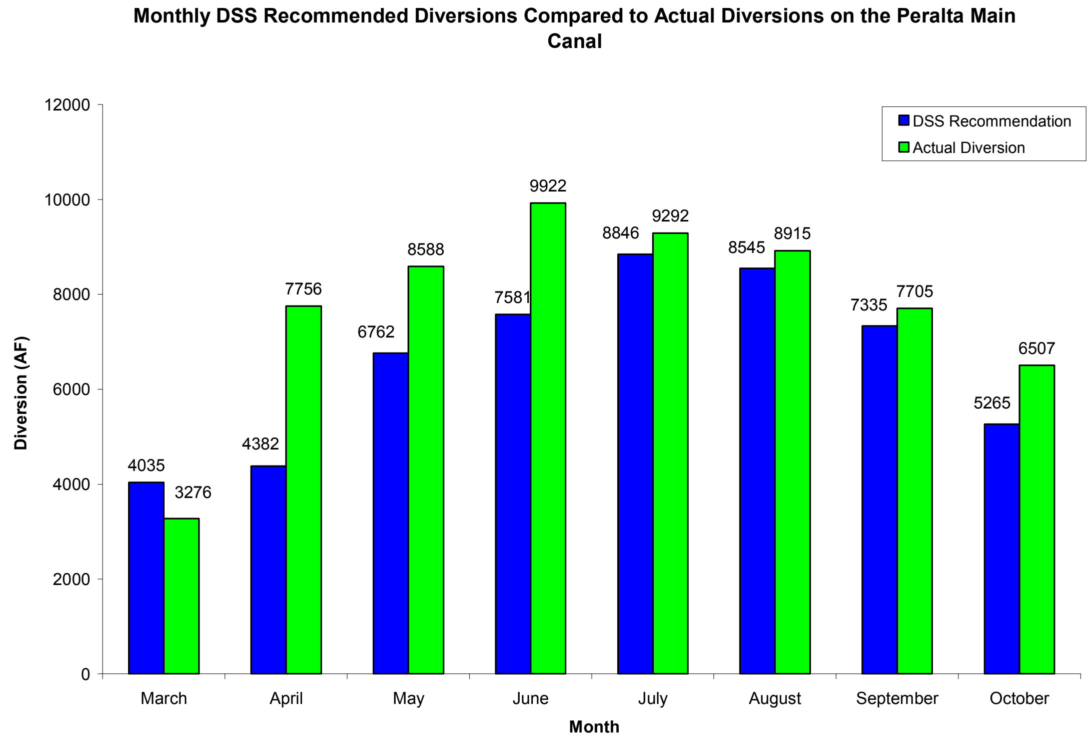


Figure 6.12: Actual Monthly Diversions and DSS Recommended Diversions for the Peralta Main Canal in 2009

The Nash Sutcliffe model efficiency statistic for the monthly diversion numbers was 0.26 indicating that there was a certain degree of agreement between the DSS recommendations and the actual diversion numbers on a monthly basis. The mean monthly difference between the actual diversions and the DSS recommended diversions was found to be 1,341 acre feet. This indicates that on average the ditch-riders and water master were able to match the recommended diversions within 1,341 acre feet on a monthly basis. The mean difference during the early part of the season from April to June was found to be 2,513 acre feet. This mean difference decreased to 607 acre feet from July to October indicating that the ditch-riders and water master were indeed able to implement scheduled water delivery calculated using the DSS more effectively as the season progressed.

The yearly diversion totals for the Peralta Main canal were also compared to the DSS recommendations. The DSS recommended yearly diversion for the Peralta Main Canal in 2009 was 52,752 acre feet. The actual diversion for the Peralta Main Canal was 61,960 acre feet. The difference in the yearly actual diversion total and the DSS suggested diversion was found to be 15%. This indicates that the diversions on the Peralta Main Canal were generally 15% higher than the diversion values recommended by the DSS. Figure 6.13 displays the comparison between the yearly totals for the actual diversion and the DSS suggested diversion. The standard deviation for the DSS monthly values was 1,827 acre feet and 2,095 acre feet for the actual diversions, indicating minimal variation in the monthly data.

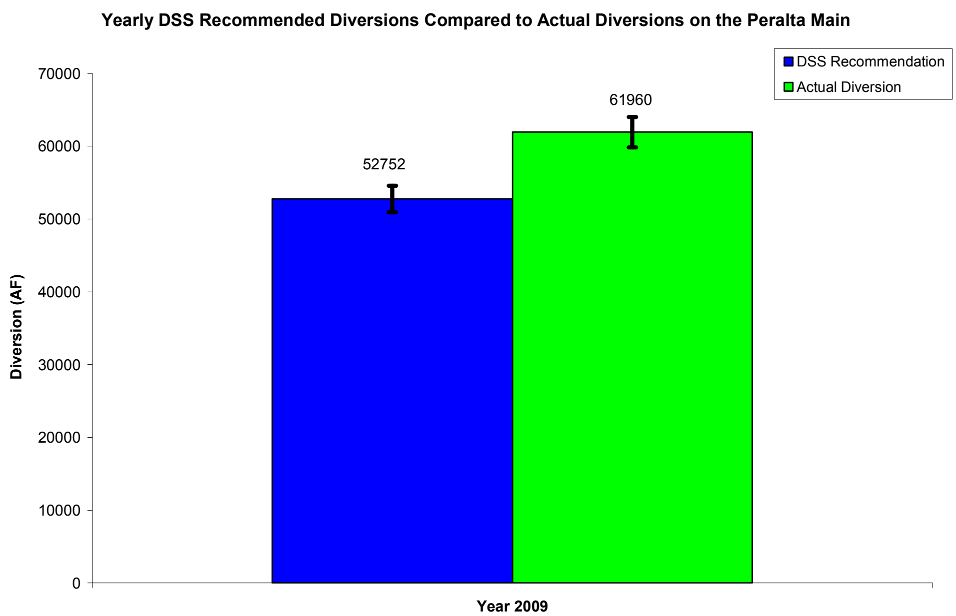


Figure 6.13: Comparison between the Yearly Total for the Actual Diversion and the DSS Suggested Diversion on the Peralta Main Canal in 2009

The cumulative actual diversions and DSS suggested diversions in acre feet for the Peralta Main Canal were also analyzed. These were analyzed to determine how well the diversions suggested by the DSS were followed as the season progressed. For the Peralta Main Canal the actual cumulative diversions were slightly higher than the DSS recommendations. A slightly higher cumulative value as the season progressed indicates that the required amount of water on a cumulative basis was supplied throughout the season and that water users were not negatively impacted by the utilization of the DSS. The Nash Sutcliffe value for the cumulative DSS modeling efficiency was 0.88 indicating that on a cumulative basis throughout the season the water master and ditch-riders were able to follow the DSS recommendations quite well. Figure 6.14 displays the comparison between the cumulative DSS diversion and actual diversion on the Peralta Main Canal.

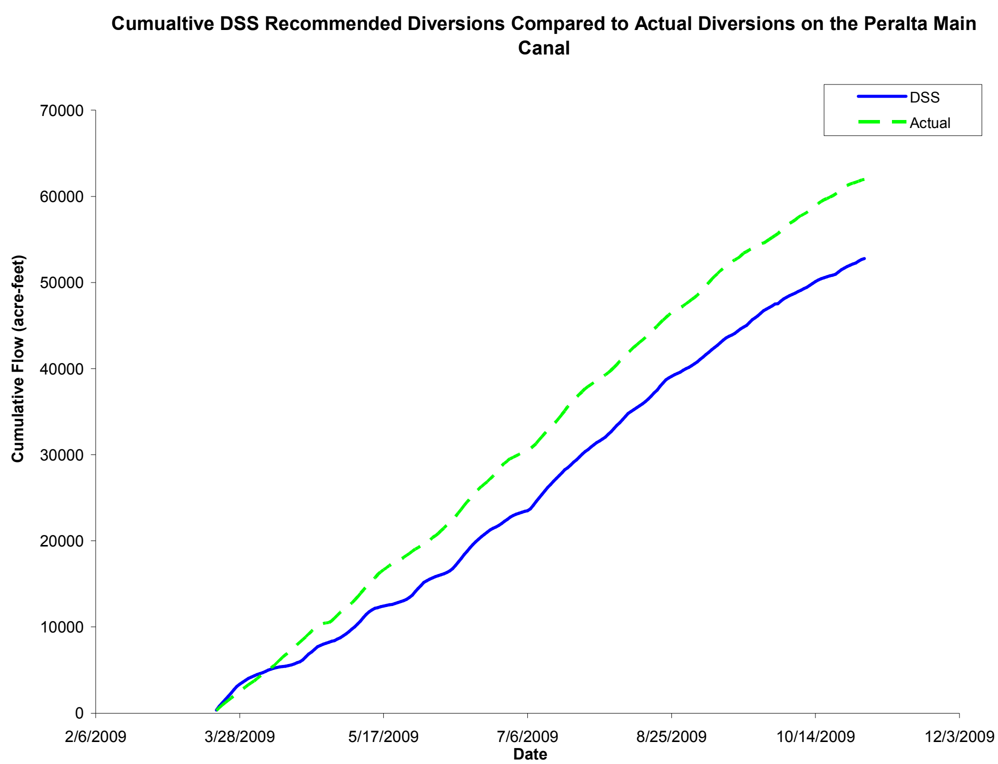


Figure 6.14: Cumulative DSS diversion and Actual Diversion on the Peralta Main Canal in 2009

The correlation between the DSS recommended flow and the actual flow utilized during the 2009 irrigation season for the Peralta Main Canal was also examined. The correlation coefficient was calculated to be 0.99 which indicates that the actual cumulative daily flow and DSS recommended flow were highly correlated. Plotting the DSS cumulative flow against the actual cumulative flow indicated that the correlation was skewed slightly higher than the ideal fit line which indicates that actual diversions were slightly higher than the DSS suggested diversions. Figure 6.15 displays the correlation between the actual and DSS recommended cumulative flow in acre feet.

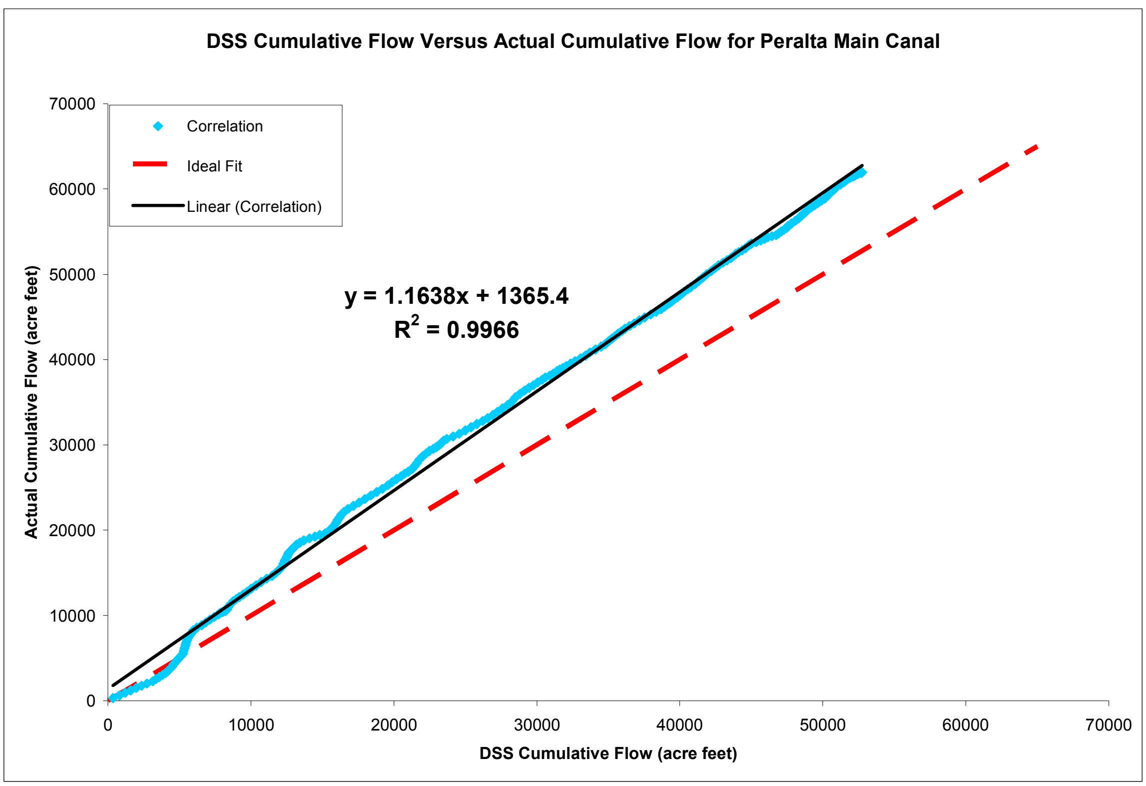


Figure 6.15: Correlation between the Actual and DSS Recommended Cumulative Flow in Acre Feet for the Peralta Main Canal in 2009

6.6.4 Peralta Acequia Diversion

Using the installed Langemann gate at the heading and SCADA telemetry it was possible to record the flow rate being delivered to the Peralta Acequia every thirty minutes during the 2009 irrigation season. These values were compared to the flow rate values suggested by the DSS water delivery calendars to access how well the ditch-rider on the Peralta Acequia was able to follow the DSS recommendations.

The first comparison that was analyzed for the Peralta Acequia diversion was the daily value of flow rate in cubic feet per second. The daily flow rate values showed significant variability but it is apparent that the ditch-rider attempted to shut down the Peralta Acequia when it was suggested by the DSS in most cases. The Peralta Acequia is often used to supplement other areas when Pueblo irrigators use water upstream and the ditch-rider could not shut the ditch entirely down for that reason. Figure 6.16 displays the daily flow rate suggested by the DSS and the actual flow rate for 2009 for the Peralta Acequia.

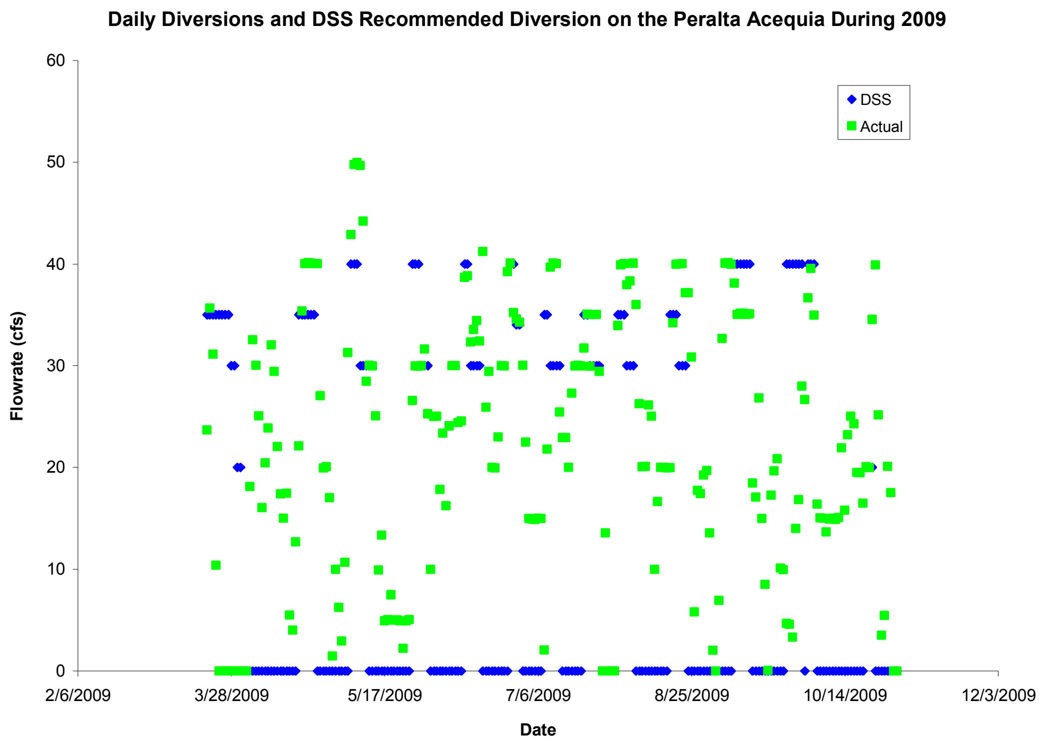


Figure 6.16: DSS Daily Flow Rate and Actual Flow Rate for Peralta Acequia in 2009.

To analyze the variability in the daily flow rate values for the Peralta Acequia the Nash Sutcliffe modeling efficiency statistic was calculated. The Nash Sutcliffe value for the fit between the modeled DSS daily flow rate and the actual daily flow rate was found to be -1.22. This indicates that on a daily basis the DSS modeled flow did not represent the actual practice sufficiently for the Peralta Acequia. There are many reasons for this and they include farming practices such as cutting and bailing, the planting of new fields, pueblo irrigators utilizing water without advance notice, and farmer's not utilizing water when it was available.

Since the Nash Sutcliffe value indicated that the DSS daily flow rate and actual daily flow rate utilized on the Peralta Acequia during 2009 showed significant variability it was deemed appropriate to analyze the monthly, yearly and cumulative daily diversions to eliminate the variability. This was deemed appropriate as the DSS creates schedules that call for irrigation water approximately every two weeks.

The actual monthly diversion values and the DSS predicted values were calculated in acre feet. For the Peralta Acequia both the actual diversion and DSS suggested monthly diversions showed a bell curve shape characteristic of a canal that is used to supply water for crop demand. The actual diversion numbers on a monthly basis were higher than the DSS suggested value in every month except March. The reason for this was that the soil moisture level at the start of the irrigation season was set to 0% RAM remaining which resulted in the model suggesting a high diversion to fill the deficit in soil moisture at the start of the season. Based on the actual diversions it appears that this assumption was conservative as the actual diversion was 554 acre feet lower than the DSS suggested diversion in March. From the analysis completed in Section 5.1.5 a value of 10% RAM remaining would have been more appropriate. Throughout the entire season the actual diversions numbers were much higher than the DSS recommended diversions. This can be attributed to the ditch-rider using the Peralta Acequia to supply water to the Hell Canyon Lateral downstream when water shortages occurred upstream during irrigation on the Isleta Pueblo Indian Reservation. Figure 6.17 displays the comparison between the actual monthly diversion and the DSS suggested diversion for the Peralta Acequia in 2009.

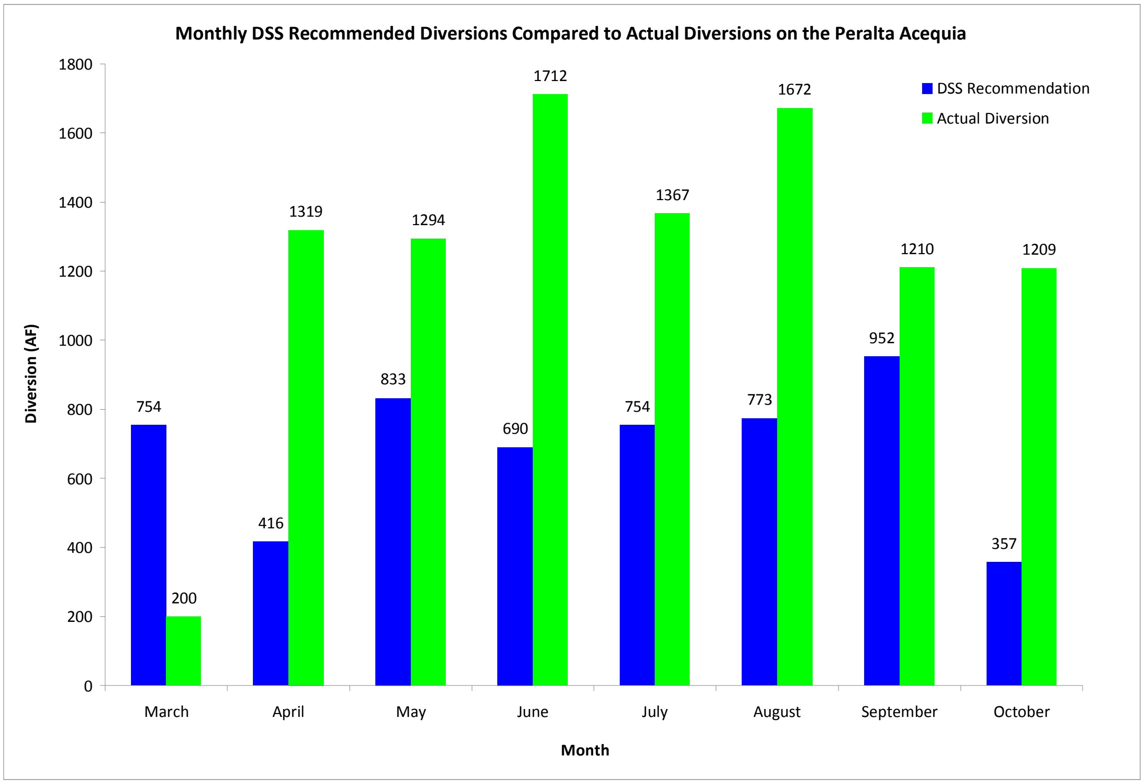


Figure 6.17: Actual Monthly Diversions and DSS Recommended Diversions for the Peralta Acequia in 2009

The mean monthly difference between the actual diversions and the DSS recommended diversions was found to be 695 acre feet. This indicates that on average the ditch-rider and water master were able to match the recommended diversions within 695 acre feet on monthly basis. The mean difference during the early part of the season from April to June was found to be 795 acre feet. This mean difference decreased to 656 acre feet from July to October indicating that the ditch-riders and water master were able to implement scheduled water delivery calculated using the DSS more effectively as the season progressed.

The yearly diversion totals for the Peralta Acequia were also compared to the DSS recommendations. The DSS recommended yearly diversion for the Peralta Acequia in 2009 was 5,529 acre feet. The actual diversion for the Peralta Main Canal was 9,982 acre feet. The difference in the yearly actual diversion total and the DSS suggested diversion was found to be 45%. This indicates that the diversion on the Peralta Acequia were generally 45% higher than the diversion values recommended by the DSS. This can be explained by the operational practice that the Peralta Acequia was used to supply water for another lateral when heavy Pueblo irrigation was occurring. Figure 6.18 displays the comparison between the yearly totals for the actual diversion and the DSS suggested diversion. The standard deviation for the DSS monthly values was 203 acre feet and 466 acre feet for the actual diversions indicating minimal variation in the monthly data.

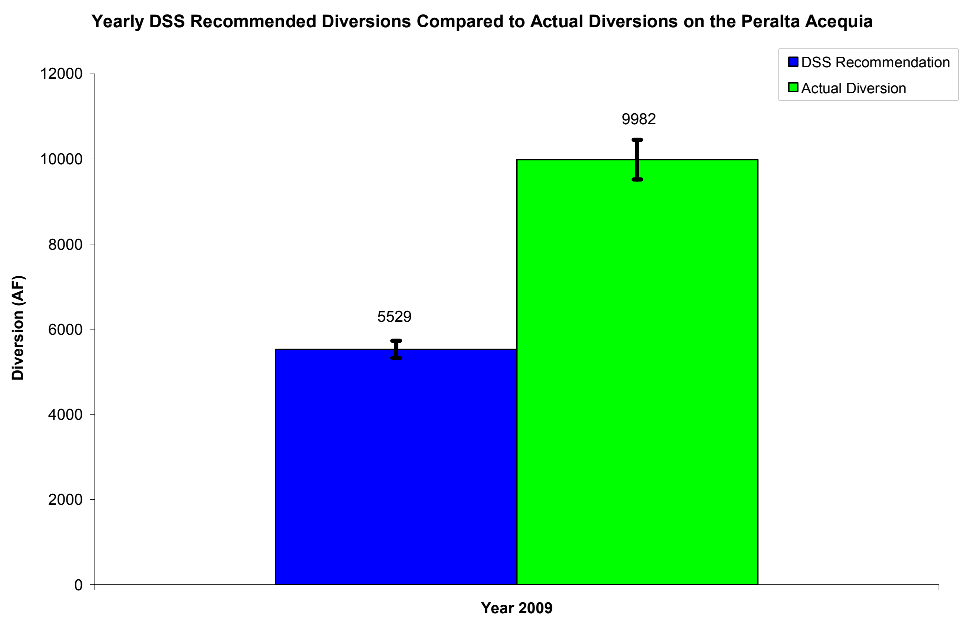


Figure 6.18: Comparison between the Yearly Total for the Actual Diversion and the DSS Suggested Diversion on the Peralta Acequia in 2009

The cumulative actual diversions and DSS suggested diversions in acre feet for the Peralta Acequia were also analyzed. These were analyzed to determine how well the diversions suggested by the DSS were followed as the season progressed. For the Peralta

Acequia the actual cumulative diversions were significantly higher than the DSS recommendations. A higher cumulative value as the season progressed indicates that much more water than needed for crop demand was diverted into the Peralta Acequia, which is explained by the operational procedures used to supply the Hell Canyon Lateral. The Nash Sutcliffe value for the cumulative DSS modeling efficiency was 0.36 indicating that on a cumulative basis throughout the season the water master and ditch-riders had difficulty following the DSS recommendations. The changes in slope are attributed to the Peralta Acequia being scheduled off. Figure 6.19 displays the comparison between the cumulative DSS diversion and actual diversion on the Peralta Main Canal.

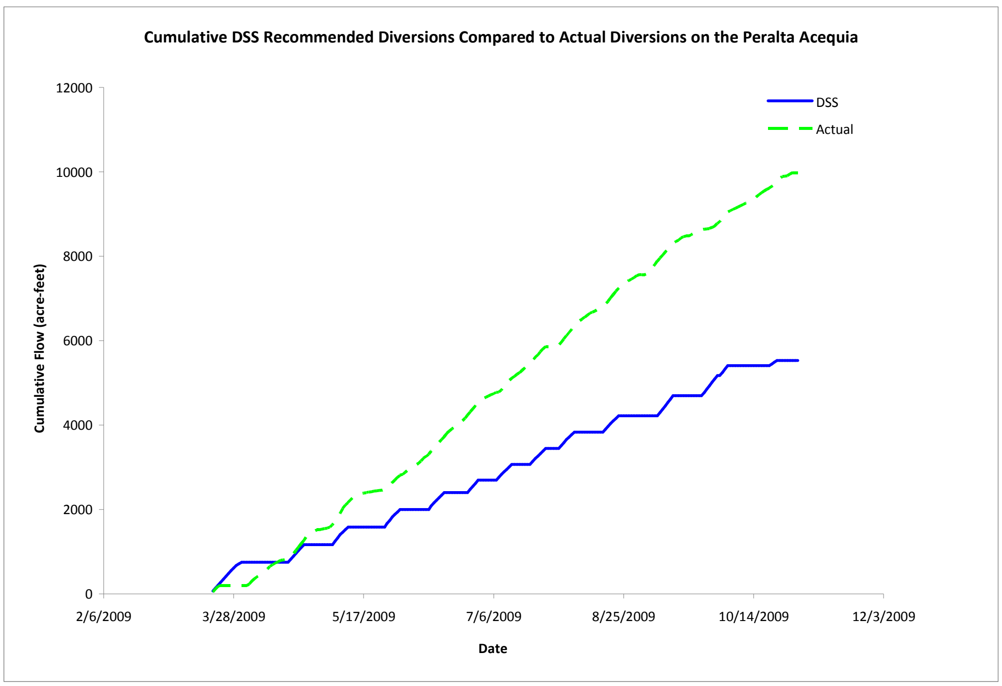


Figure 6.19: Cumulative DSS diversion and Actual Diversion on the Peralta Acequia in 2009

The correlation between the DSS recommended flow and the actual flow utilized during the 2009 irrigation season for the Peralta Acequia was also examined. The correlation coefficient was calculated to be 0.99 which indicates that the actual cumulative daily flow and DSS recommended flow were highly correlated. Plotting the DSS cumulative flow against the actual cumulative flow indicated that the correlation was skewed significantly higher than the ideal fit line which indicates that actual diversions were much higher than the DSS suggested diversions. Figure 6.20 displays the correlation between the actual and DSS recommended cumulative flow in acre feet.

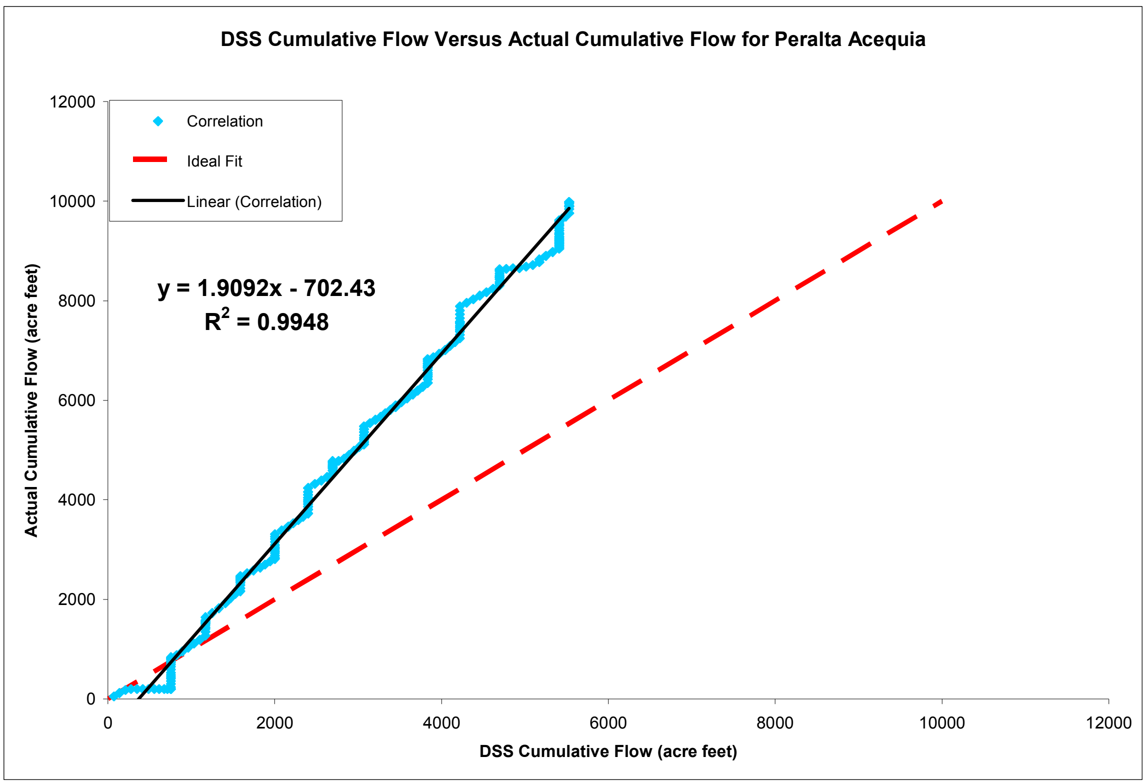


Figure 6.20: Correlation between the Actual and DSS Recommended Cumulative Flow in Acre Feet for the Peralta Acequia in 2009

6.6.5 La Constancia Acequia Diversion

Utilizing the installed Langemann gate at the heading and SCADA telemetry it was possible to record the flow rate being delivered to the La Constancia Acequia every thirty minutes during the 2009 irrigation season. These values were compared to the flow rate values suggested by the DSS water delivery calendars to access how well the ditch-riders and water master were able to follow the DSS recommendations.

The first comparison that was analyzed for the La Constancia Acequia diversion was the daily value of flow rate in cubic feet per second. The daily flow rate values showed significant variability although the DSS and actual diversion numbers showed the same general trend. It is apparent that the ditch-rider tried to shut down the La Constancia Acequia according to the DSS schedule recommendations. Figure 6.21 displays the daily flow rate suggested by the DSS and the actual flow rate for 2009.

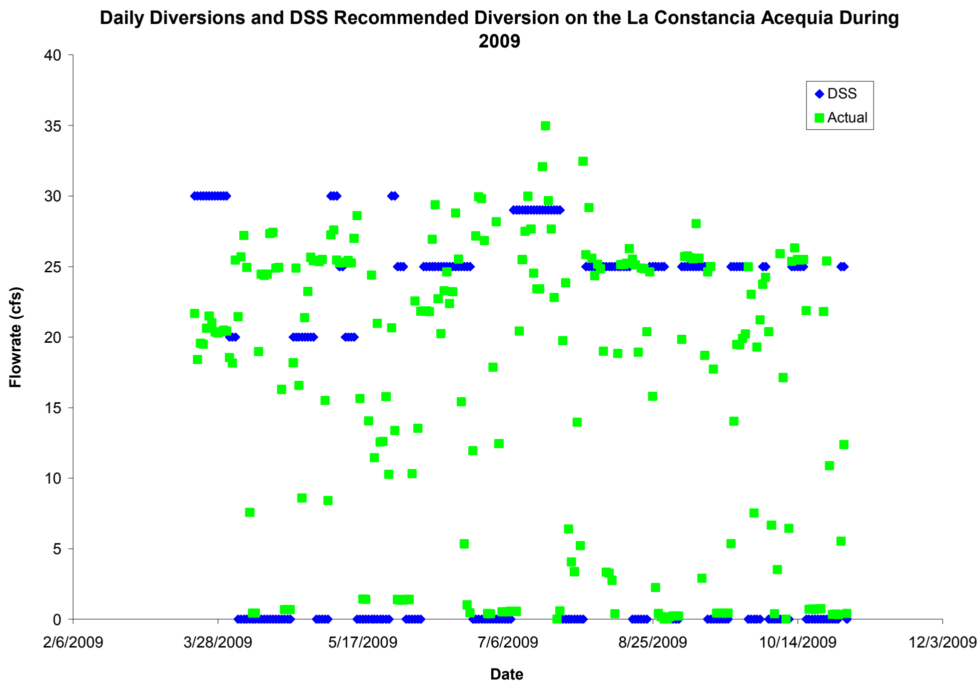


Figure 6.21: DSS Daily Flow Rate and Actual Flow Rate for La Constancia Acequia in 2009.

To analyze the variability in the daily flow rate values for the Peralta Main Canal the Nash Sutcliffe modeling efficiency statistic was calculated. The Nash Sutcliffe value for the fit between the modeled DSS daily flow rate and the actual daily flow rate was found to be -0.91. This indicates that on a daily basis the DSS modeled flow did not represent the actual practice sufficiently.

Since the Nash Sutcliffe value indicated that the DSS daily flow rate and actual daily flow rate utilized on the La Constancia Acequia during 2009 showed significant variability it was deemed appropriate to analyze the monthly, yearly and cumulative daily diversions to eliminate the variability. This was deemed appropriate as the DSS creates schedules that call for irrigation water approximately every two weeks.

The actual monthly diversion values and the DSS predicted values were calculated in acre feet. For the La Constancia Acequia the DSS suggested monthly diversions showed a bell curve shape characteristic of a canal that is used to supply water for crop demand. The actual diversions showed a linear trend decreasing toward the end of the season. The actual diversion numbers on a monthly basis were higher than the DSS suggested value except in March and August. The reason for this difference in March was that the soil moisture level at the start of the irrigation season was set to 0% RAM remaining which resulted in the model suggesting a high diversion to fill the deficit in soil moisture at the start of the season. Based on the actual diversions it appears that this assumption was conservative as the actual diversion was 230 acre feet lower than the DSS suggested diversion in March. From the analysis completed in Section 5.1.5 a value of 10% RAM remaining would have been more appropriate. In August the actual diversion was 60 acre feet lower and this can be attributed to significant rainfall during the monsoon. The three months of April, May, and June towards the beginning of the season showed the large differences between the DSS recommendations and actual diversions. During the later half of the season the difference between the actual diversions and the DSS recommendation decreased. The reason for this difference was that the ditch-rider and water master on the La Constancia Acequia became more comfortable and adept at implementing the water delivery schedules suggested by the DSS. Figure 6.22 displays the comparison between the actual monthly diversion and the DSS suggested diversion.

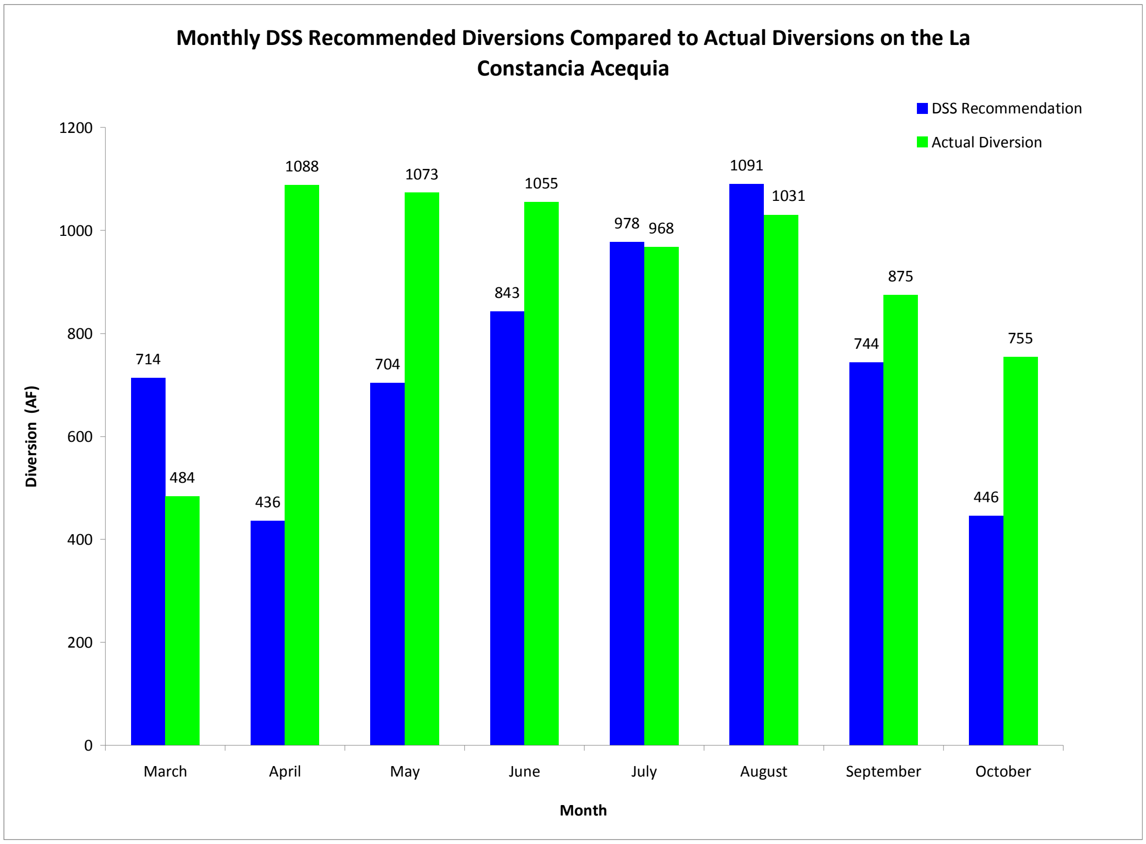


Figure 6.22: Actual Monthly Diversions and DSS Recommended Diversions for the La Constancia Acequia in 2009

The mean monthly difference between the actual diversions and the DSS recommended diversions was found to be 247 acre feet. This indicates that on average the ditch-riders and water master were able to match the recommended diversions within 247 acre feet on monthly basis. The mean difference during the early part of the season from April to June was found to be 411 acre feet. This mean difference decreased to 93 acre feet from July to October indicating that the ditch-rider and water master were able to implement scheduled water delivery calculated using the DSS more efficiently as the season progressed.

The yearly diversion totals for the La Constancia Acequia were also compared to the DSS recommendations. The DSS recommended yearly diversion for the La Constancia Acequia in 2009 was 5,955 acre feet. The actual diversion for the La Constancia was 7,330 acre feet. The difference in the yearly actual diversion total and the DSS suggested diversion was found to be 19%. This indicates that the diversions on the La Constancia Acequia were generally 19% higher than the diversion values recommended by the DSS. Figure 6.23 displays the comparison between the yearly totals for the actual diversion and the DSS suggested diversion. The standard deviation for the DSS monthly values was 230 acre feet and 208 acre feet for the actual diversions indicating minimal variation in the monthly data.

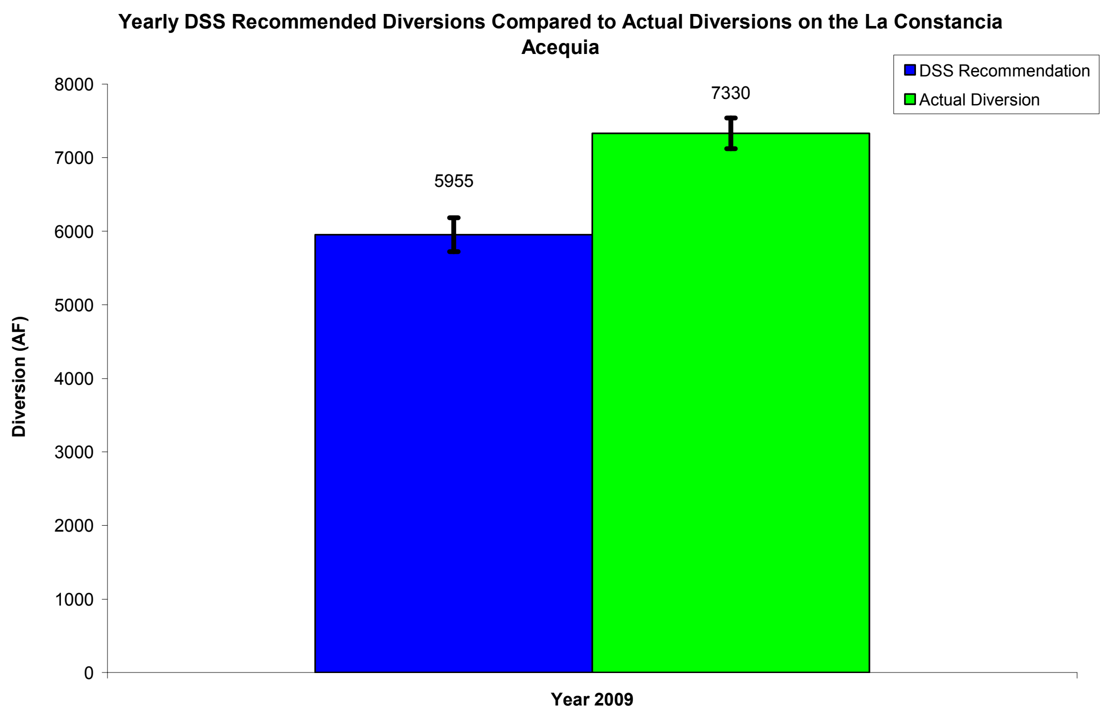


Figure 6.23: Comparison between the Yearly Total for the Actual Diversion and the DSS Suggested Diversion on the La Constancia Acequia in 2009

The cumulative actual diversions and DSS suggested diversions in acre feet for the La Constancia Acequia were also analyzed. These were analyzed to determine how well the diversions suggested by the DSS were followed as the season progressed. For the La Constancia the actual cumulative diversions were slightly higher than the DSS recommendations. A slightly higher cumulative value as the season progressed indicates that the required amount of water on a cumulative basis was supplied throughout the season and that water users were not negatively impacted by the utilization of the DSS. The Nash Sutcliffe value for the cumulative DSS modeling efficiency was 0.82 indicating that on a cumulative basis throughout the season the water master and ditch-riders were able to follow the DSS recommendations quite well. Figure 6.24 displays the comparison between the cumulative DSS diversion and actual diversion on the La Constancia Acequia.

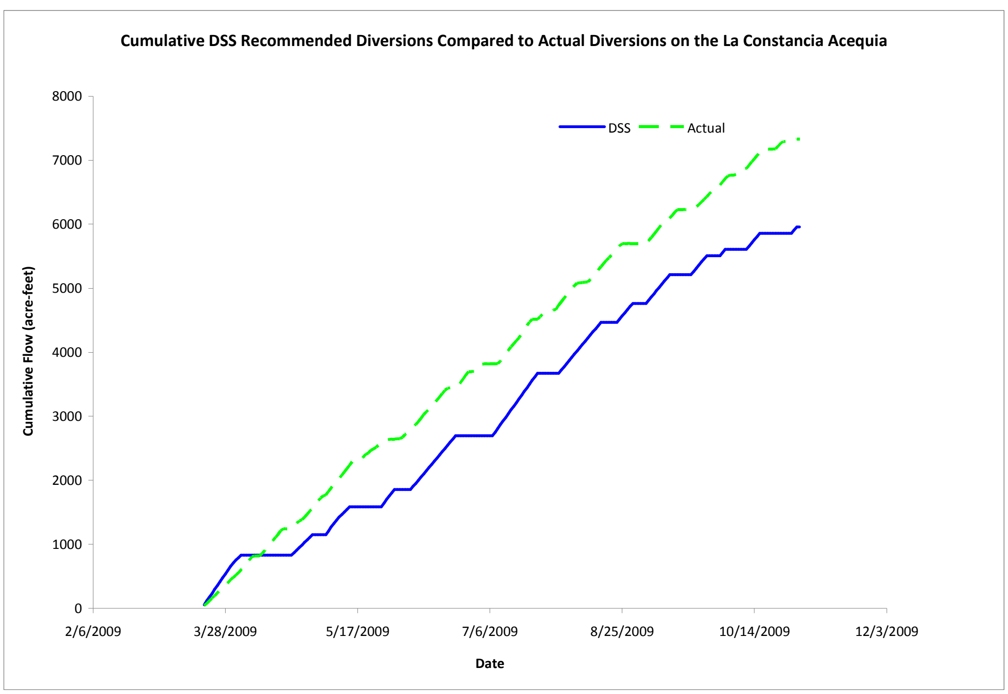


Figure 6.24: Cumulative DSS diversion and Actual Diversion on the La Constancia Acequia in 2009

The correlation between the DSS recommended flow and the actual flow utilized during the 2009 irrigation season for the La Constancia was also examined. The correlation coefficient was calculated to be 0.99 which indicates that the actual cumulative daily flow and DSS recommended flow were highly correlated. Plotting the DSS cumulative flow against the actual cumulative flow indicated that the correlation was skewed higher than the ideal fit line which indicates that actual diversions were slightly higher than the DSS suggested diversions. Figure 6.25 displays the correlation between the actual and DSS recommended cumulative flow in acre feet for the La Constancia Acequia.

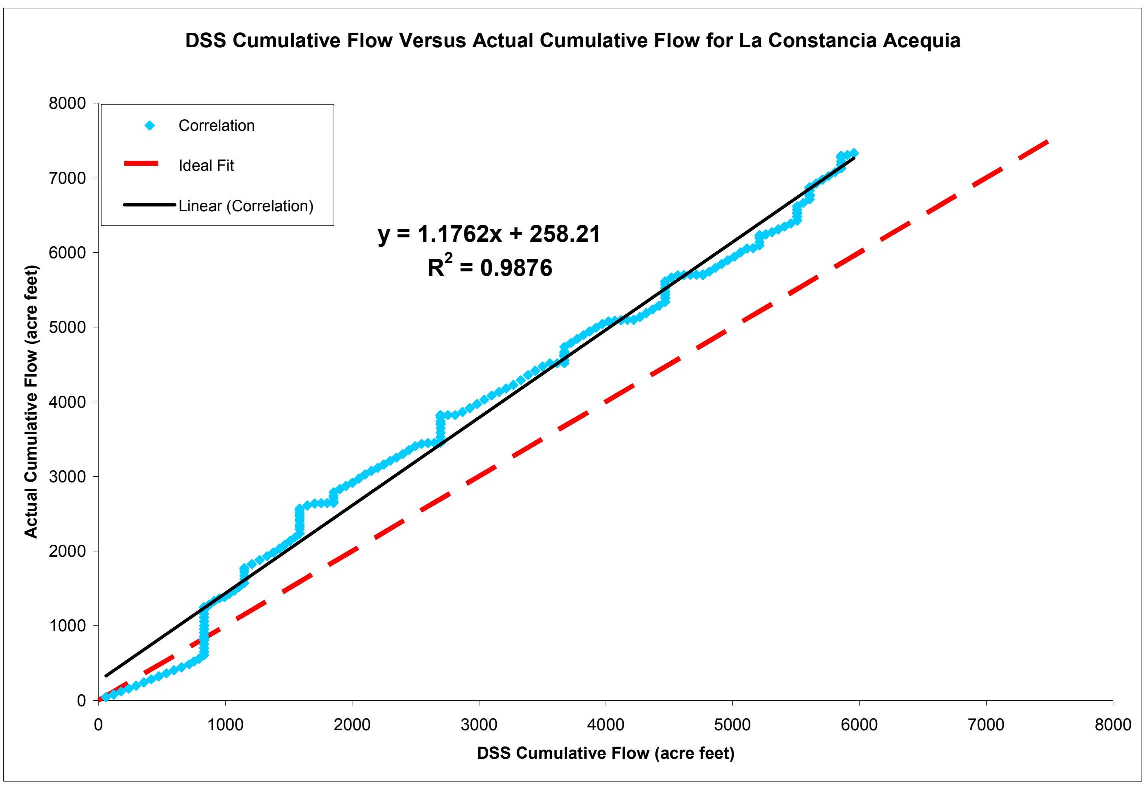


Figure 6.25: Correlation between the Actual and DSS Recommended Cumulative Flow in Acre Feet for the La Constancia Acequia in 2009

6.6.6 Otero Lateral Diversion

With the installed Langemann gate at the heading and SCADA telemetry it was possible to record the flow rate being delivered to the Otero Lateral every thirty minutes during the 2009 irrigation season. These values were compared to the flow rate values suggested by the DSS water delivery calendars to access how well the ditch-riders and water master were able to follow the DSS recommendations.

The first comparison that was analyzed for the Otero Lateral diversion was the daily value of flow rate in cubic feet per second. The daily flow rate values showed significant variability although the DSS and actual diversion numbers showed the same general trend. Figure 6.26 displays the daily flow rate suggested by the DSS and the actual flow rate for 2009.

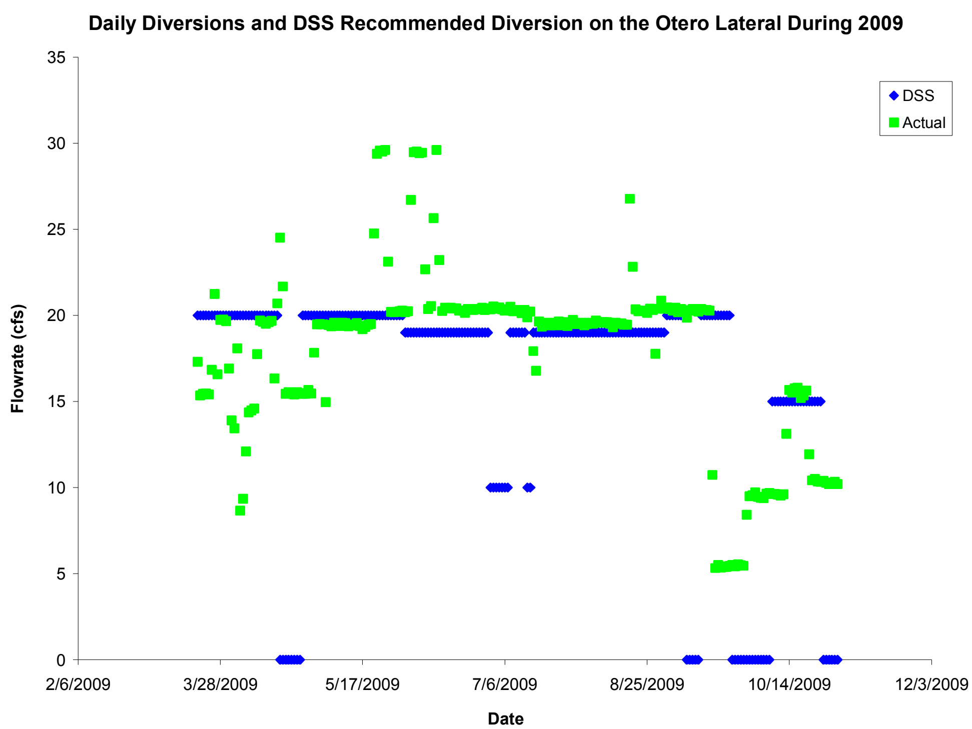


Figure 6.26: DSS Daily Flow Rate and Actual Flow Rate for Otero Lateral in 2009.

To analyze the variability in the daily flow rate values for the Peralta Main Canal the Nash Sutcliffe modeling efficiency statistic was calculated. The Nash Sutcliffe value for the fit between the modeled DSS daily flow rate and the actual daily flow rate was found to be -0.79.

Since the Nash Sutcliffe value indicated that the DSS daily flow rate and actual daily flow rate utilized on the Otero Lateral during 2009 showed significant variability it was deemed appropriate to analyze the monthly, yearly and cumulative daily diversions to eliminate the variability. This was deemed appropriate as the DSS creates schedules that call for irrigation water approximately every two weeks.

The actual monthly diversion values and the DSS predicted values were calculated in acre feet. For the Otero Lateral both the DSS suggested monthly diversions and actual diversions showed a bell curve shape characteristic of a canal that is used to supply water for crop demand. The actual diversion numbers on a monthly basis were higher than the DSS suggested value in March. The reason for this difference in March was that the soil moisture level at the start of the irrigation season was set to 0% RAM remaining which resulted in the model suggesting a high diversion to fill the deficit in soil moisture at the start of the season. Based on the actual diversions it appears that this assumption was conservative as the actual diversion was 60 acre feet lower than the DSS suggested diversion in March. Based on the difference between the DSS recommended and actual monthly diversion it appears that the ditch-rider and water master were able to effectively follow the DSS recommendations throughout the season with no trends indicating improvement during the later half of the season. Figure 6.27 displays the comparison between the actual monthly diversion and the DSS suggested diversion.

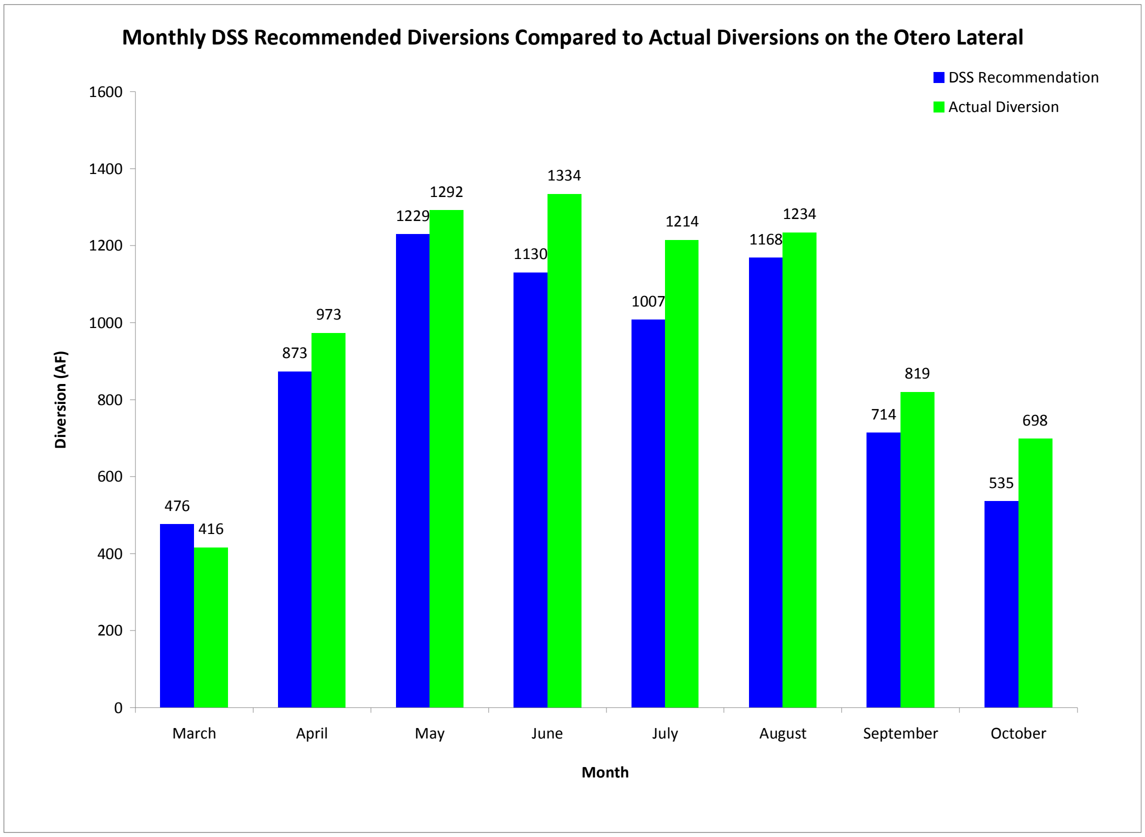


Figure 6.27: Actual Monthly Diversions and DSS Recommended Diversions for the Otero Lateral in 2009

The mean monthly difference between the actual diversions and the DSS recommended diversions was found to be 121 acre feet. This indicates that on average the ditch-riders and water master were able to match the recommended diversions within 121 acre feet on monthly basis.

The yearly diversion totals for the Otero Lateral were also compared to the DSS recommendations. The DSS recommended yearly diversion for the Otero Lateral in 2009 was 7,133 acre feet. The actual diversion for the Otero Lateral was 7,981 acre feet.

The difference in the yearly actual diversion total and the DSS suggested diversion was found to be 11%. This indicates that the diversions on the Otero Lateral were generally 11% higher than the diversion values recommended by the DSS. Figure 6.28 displays the comparison between the yearly totals for the actual diversion and the DSS suggested diversion. The standard deviation for the DSS monthly values was 291 acre feet and 330 acre feet for the actual diversions indicating minimal variation in the monthly data.

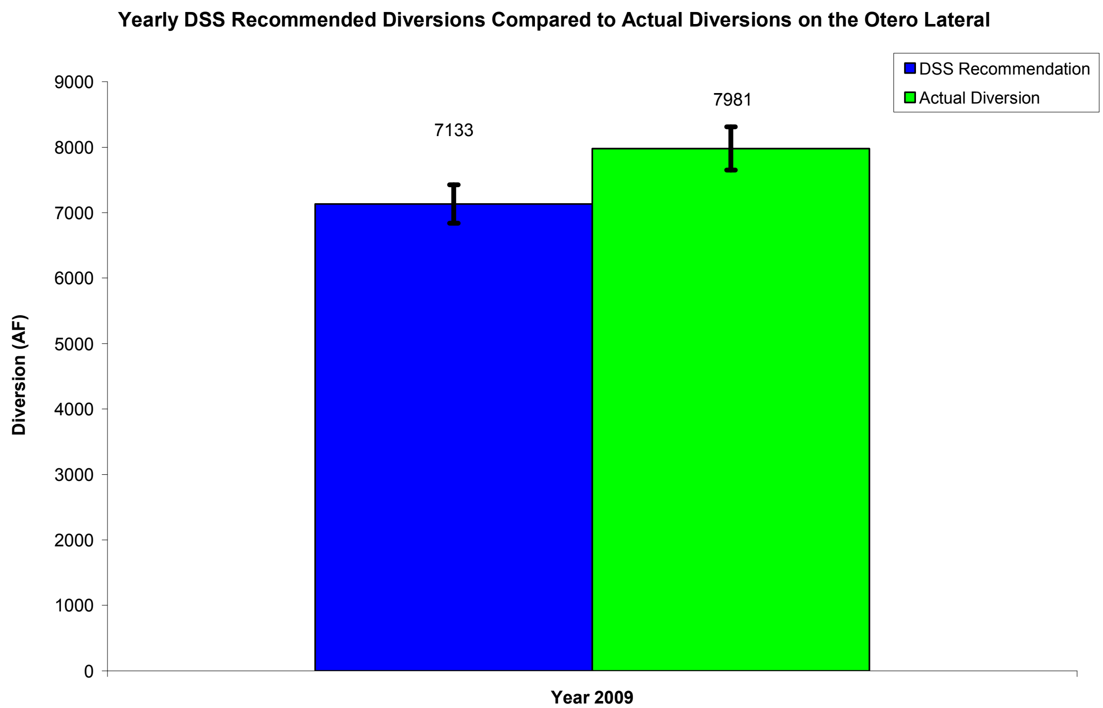


Figure 6.28: Comparison between the Yearly Total for the Actual Diversion and the DSS Suggested Diversion on the Otero Lateral in 2009

The cumulative actual diversions and DSS suggested diversions in acre feet for the Otero Lateral were also analyzed. These were analyzed to determine how well the diversions suggested by the DSS were followed as the season progressed. For the Otero Lateral the actual cumulative diversions were slightly higher but nearly identical to the

DSS recommendations. A convergence of the two curves indicates that the diversions on the Otero Lateral closely followed the DSS recommendation. The Nash Sutcliffe value for the cumulative DSS modeling efficiency was 0.96 indicating that on a cumulative basis throughout the season, the water master and ditch-rider were able to follow the DSS recommendations nearly perfectly. Figure 6.29 displays the comparison between the cumulative DSS diversion and actual diversion on the Otero Lateral.

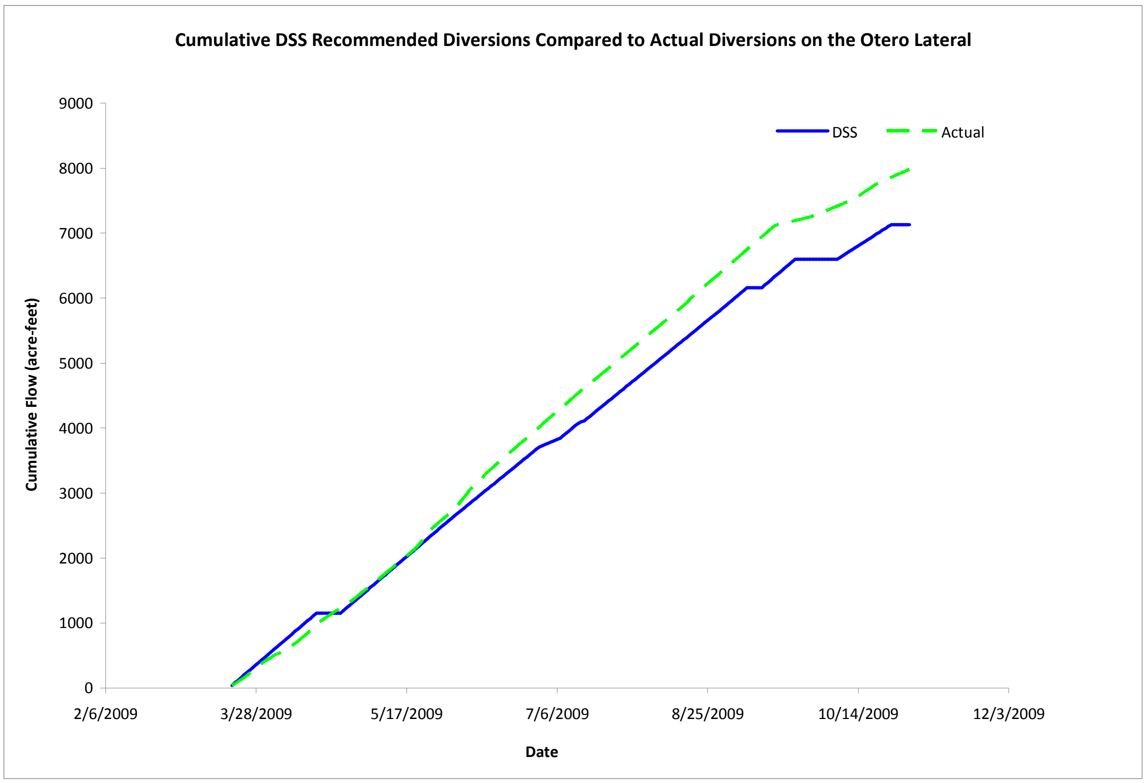


Figure 6.29: Cumulative DSS diversion and Actual Diversion on the Otero Lateral in 2009

The correlation between the DSS recommended flow and the actual flow utilized during the 2009 irrigation season for the Otero Lateral was also examined. The correlation coefficient was calculated to be 0.99 which indicates that the actual cumulative daily flow and DSS recommended flow were highly correlated. Plotting the DSS cumulative flow against the actual cumulative flow indicated that the correlation was nearly the same as the ideal fit line, which indicates that actual diversions matched the DSS suggested diversions. Figure 6.30 displays the correlation between the actual and DSS recommended cumulative flow in acre feet for the Otero Lateral.

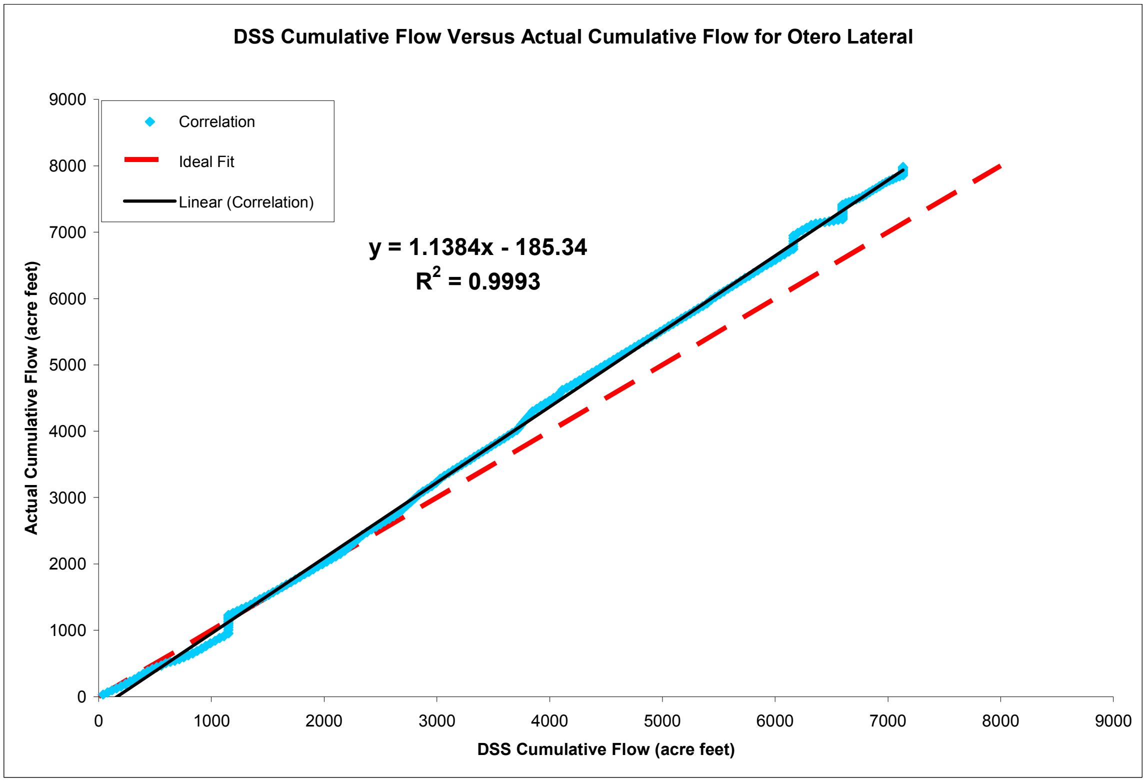


Figure 6.30: Correlation between the Actual and DSS Recommended Cumulative Flow in Acre Feet for the Otero Lateral in 2009

6.6.7 Tome Acequia Diversion

Using the installed Langemann gate at the heading and SCADA telemetry it was possible to record the flow rate being delivered to the Tome Acequia every thirty minutes during the 2009 irrigation season. These values were compared to the flow rate values suggested by the DSS water delivery calendars to access how well the ditch-rider and water master were able to follow the DSS recommendations.

The first comparison that was analyzed for the Tome Acequia diversion was the daily value of flow rate in cubic feet per second. The daily flow rate values showed significant variability although the DSS and actual diversion numbers showed the same general trend. It appears that the ditch-rider had difficulty shutting off the Tome Acequia when it was suggested by the DSS schedules. Figure 6.31 displays the daily flow rate suggested by the DSS and the actual flow rate for 2009.

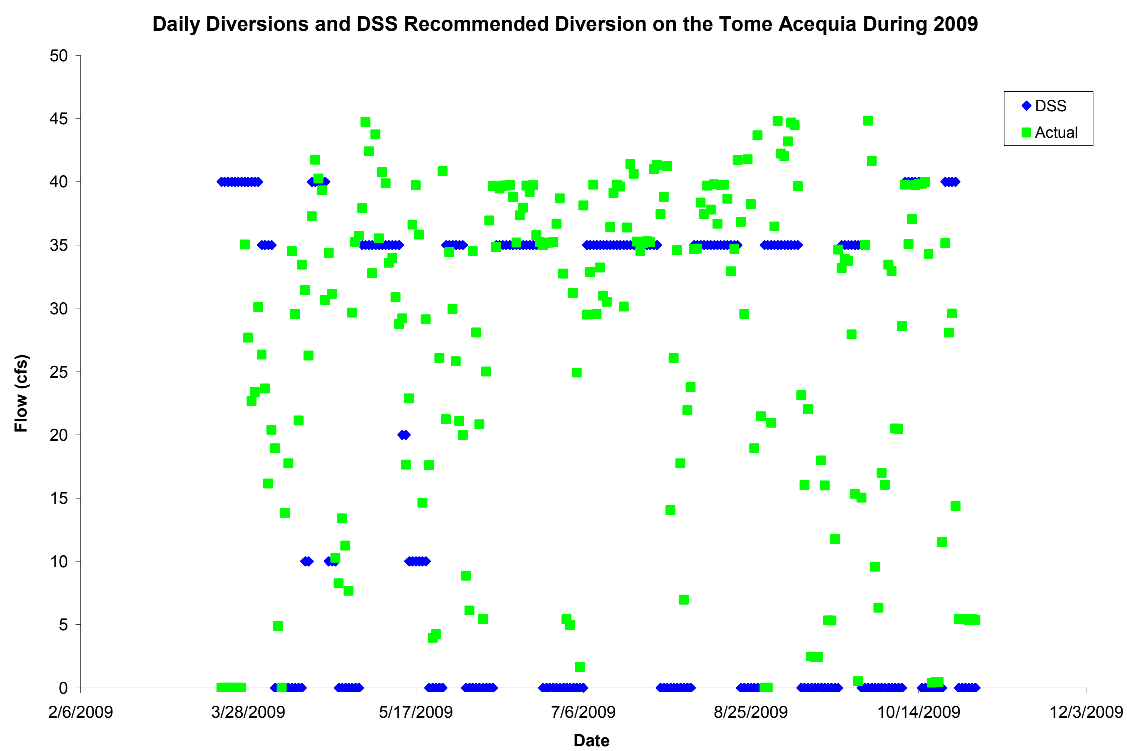


Figure 6.31: DSS Daily Flow Rate and Actual Flow Rate for Tome Acequia in 2009.

To analyze the variability in the daily flow rate values for the Peralta Main Canal the Nash Sutcliffe modeling efficiency statistic was calculated. The Nash Sutcliffe value for the fit between the modeled DSS daily flow rate and the actual daily flow rate was found to be -1.18. This indicates that on a daily basis the DSS modeled flow did not represent the actual practice sufficiently.

Since the Nash Sutcliffe value indicated that the DSS daily flow rate and actual daily flow rate utilized on the Tome Acequia during 2009 showed significant variability it was deemed appropriate to analyze the monthly, yearly and cumulative daily diversions to eliminate the variability. This was deemed appropriate as the DSS creates schedules that call for irrigation water approximately every two weeks.

The actual monthly diversion values and the DSS predicted values were calculated in acre feet. For the Tome Acequia both the actual diversion and DSS suggested monthly diversions showed a bell curve shape characteristic of a canal that is used to supply water for crop demand. The actual diversion numbers on a monthly basis were higher than the DSS suggested value in every month except March. The reason for this was that the soil moisture level at the start of the irrigation season was set to 0% RAM remaining which resulted in the model suggesting a high diversion to fill the deficit in soil moisture at the start of the season. Based on the actual diversions it appears that this assumption was conservative as the actual diversion was 677 acre feet lower than the DSS suggested diversion in March. From the analysis completed in Section 5.1.5 a value of 10% RAM remaining would have been more appropriate. Overall, the monthly values utilized by the ditch-rider on the Tome Acequia were consistently higher than the suggested DSS diversion. Figure 6.32 displays the comparison between the actual monthly diversion and the DSS suggested diversion.

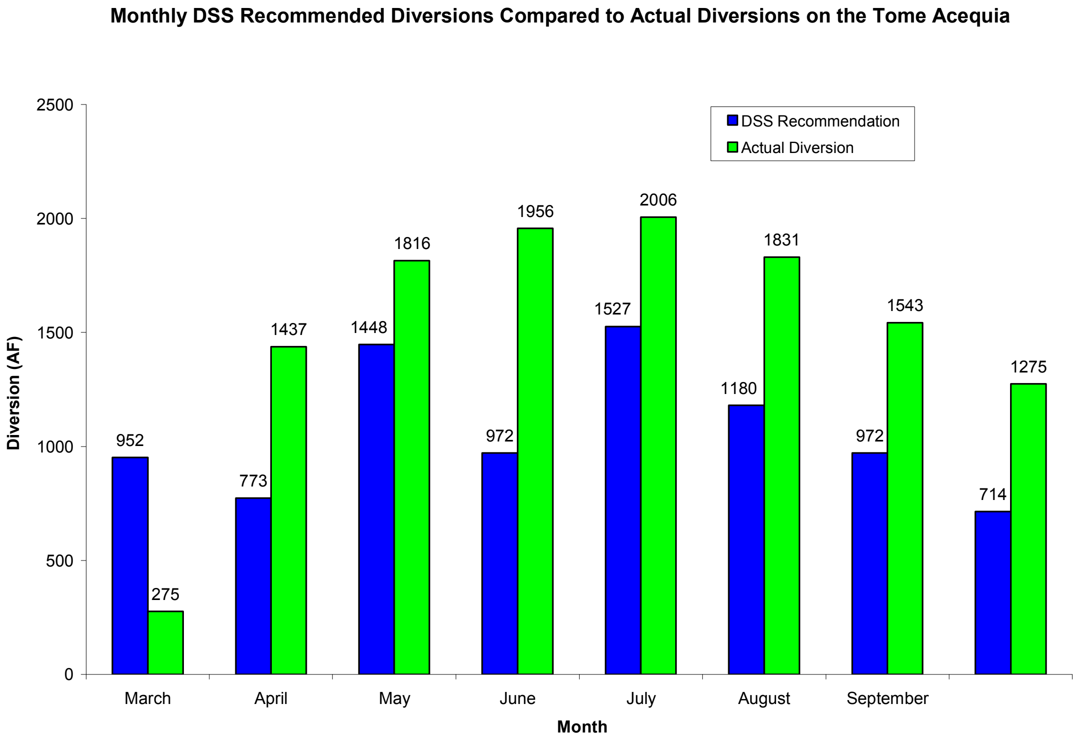


Figure 6.32: Actual Monthly Diversions and DSS Recommended Diversions for the Tome Acequia in 2009

The mean monthly difference between the actual diversions and the DSS recommended diversions was found to be 629 acre feet. This indicates that on average the ditch-riders and water master were able to match the recommended diversions within 629 acre feet on monthly basis. The comparison of mean monthly diversions does not indicate that the ditch-rider was able to implement scheduled water delivery calculated using the DSS more effectively as the season progressed. The reason for this can be attributed to the ditch-rider in the Tome Acequia service area being new during the 2009 season and having difficulty assessing and managing his service area.

The yearly diversion totals for the Tome Acequia were also compared to the DSS recommendations. The DSS recommended yearly diversion for the Tome Acequia in

2009 was 8,537 acre feet. The actual diversion for the Tome Acequia was 12,139 acre feet. The difference in the yearly actual diversion total and the DSS suggested diversion was found to be 30%. This indicates that the diversion on the Tome Acequia were generally 30% higher than the diversion values recommended by the DSS. Figure 6.33 displays the comparison between the yearly totals for the actual diversion and the DSS suggested diversion. The standard deviation for the DSS monthly values was 296 acre feet and 564 acre feet for the actual diversions indicating minimal variation in the monthly data.

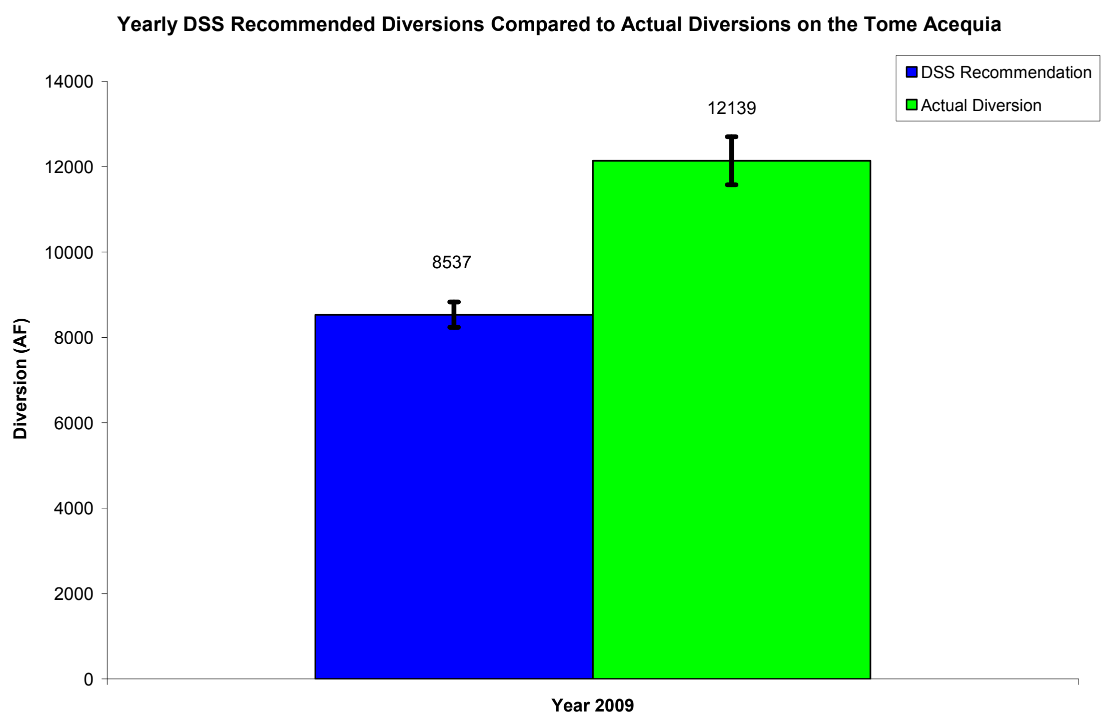


Figure 6.33: Comparison between the Yearly Total for the Actual Diversion and the DSS Suggested Diversion on the Tome Acequia in 2009

The cumulative actual diversions and DSS suggested diversions in acre feet for the Tome Acequia were also analyzed. These were analyzed to determine how well the diversions suggested by the DSS were followed as the season progressed. For the Tome

Acequia the actual cumulative diversions were higher than the DSS recommendations. A higher cumulative value as the season progressed indicates that the required amount of water on a cumulative basis was supplied throughout the season and that water users were not negatively impacted by the utilization of the DSS. The Nash Sutcliffe value for the cumulative DSS modeling efficiency was 0.74 indicating that on a cumulative basis throughout the season the ditch-rider was able to follow the DSS recommendations to a certain degree. Figure 6.34 displays the comparison between the cumulative DSS diversion and actual diversion on the Tome Acequia.

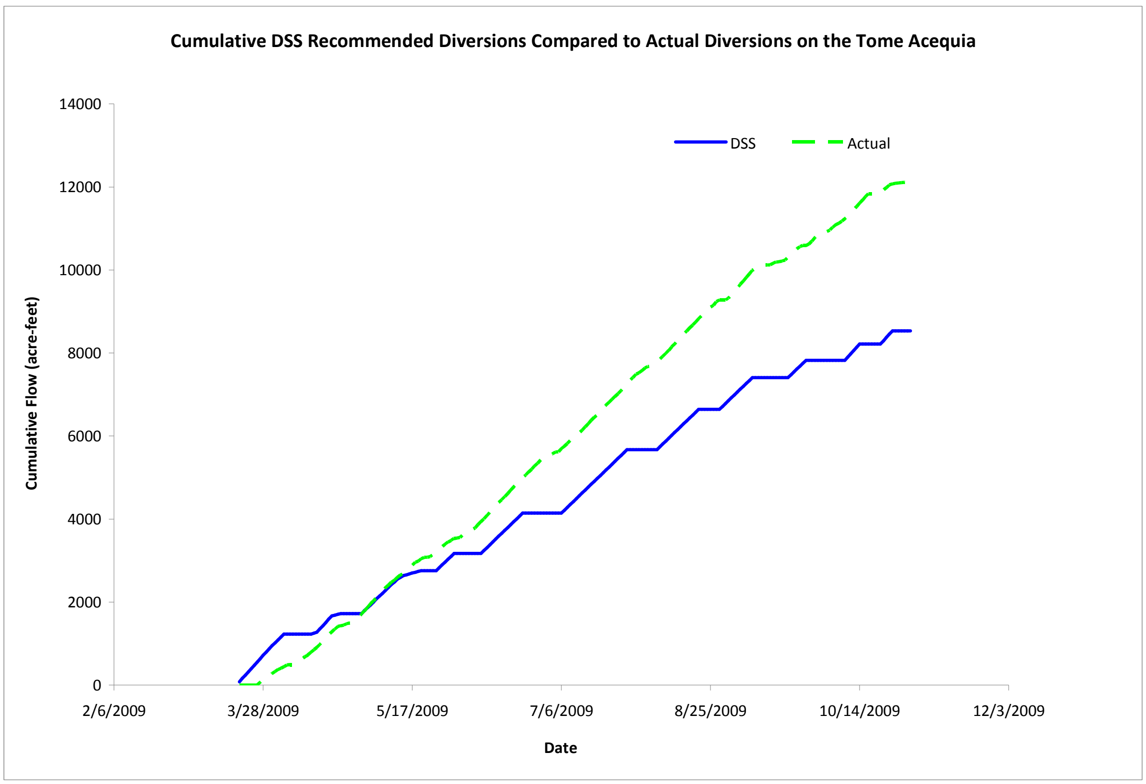


Figure 6.34: Cumulative DSS diversion and Actual Diversion on the Tome Acequia in 2009

The correlation between the DSS recommended flow and the actual flow utilized during the 2009 irrigation season for the Tome Acequia was also examined. The correlation coefficient was calculated to be 0.99 which indicates that the actual cumulative daily flow and DSS recommended flow were highly correlated. Plotting the DSS cumulative flow against the actual cumulative flow indicated that the correlation was skewed significantly higher than the ideal fit line which indicates that actual diversions were higher than the DSS suggested diversions. Figure 6.35 displays the correlation between the actual and DSS recommended cumulative flow in acre feet.

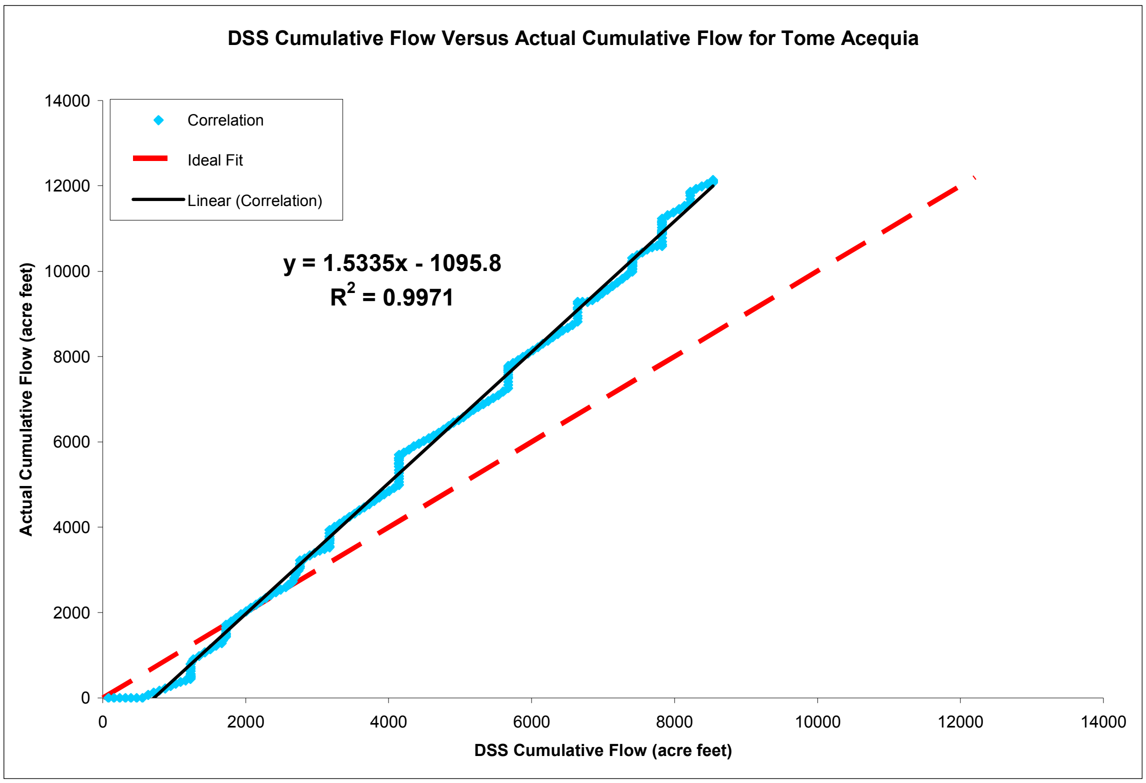


Figure 6.35: Correlation between the Actual and DSS Recommended Cumulative Flow in Acre Feet for the Tome Acequia in 2009

6.6.8 Valencia Acequia Diversion

Through the use of to the installed Langemann gate at the heading and SCADA telemetry it was possible to record the flow rate being delivered to the Valencia Acequia every thirty minutes during the 2009 irrigation season. These values were compared to the flow rate values suggested by the DSS water delivery calendars to access how well the ditch-riders and water masters were able to follow the DSS recommendations.

The first comparison that was analyzed for the Valencia Acequia diversion was the daily value of flow rate in cubic feet per second. The daily flow rate values showed significant variability although the DSS and actual diversion numbers showed the same general trend. Figure 6.36 displays the daily flow rate suggested by the DSS and the actual flow rate for 2009.

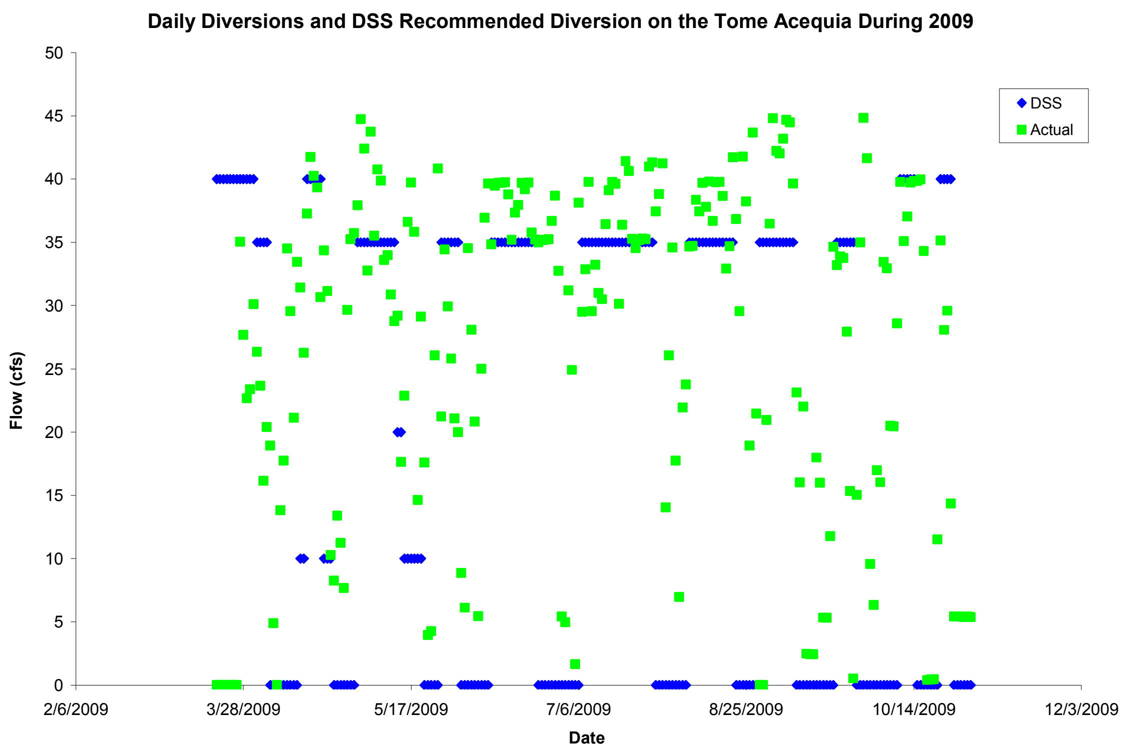


Figure 6.36: DSS Daily Flow Rate and Actual Flow Rate for Valencia Acequia in 2009.

To analyze the variability in the daily flow rate values for the Peralta Main Canal the Nash Sutcliffe modeling efficiency statistic was calculated. The Nash Sutcliffe value for the fit between the modeled DSS daily flow rate and the actual daily flow rate was found to be -0.97. This indicates that on a daily basis the DSS modeled flow did not represent the actual practice sufficiently.

Since the Nash Sutcliffe value indicated that the DSS daily flow rate and actual daily flow rate utilized on the Valencia Acequia during 2009 showed significant variability it was deemed appropriate to analyze the monthly, yearly and cumulative daily diversions to eliminate the variability. This was deemed appropriate as the DSS creates schedules that call for irrigation water approximately every two weeks.

The actual monthly diversion values and the DSS predicted values were calculated in acre feet. For the Valncia Acequia both the actual diversion and DSS suggested monthly diversions showed a bell curve shape characteristic of a canal that is used to supply water for crop demand. The actual diversion numbers on a monthly basis were higher than the DSS suggested value in every month except March. The reason for this was that the soil moisture level at the start of the irrigation season was set to 0% RAM remaining which resulted in the model suggesting a high diversion to fill the deficit in soil moisture at the start of the season. Based on the actual diversions it appears that this assumption was conservative as the actual diversion was 117 acre feet lower than the DSS suggested diversion in March. Overall, the monthly values utilized by the ditch-rider on the Valencia Acequia were consistently higher than the suggested DSS diversion. Figure 6.37 displays the comparison between the actual monthly diversion and the DSS suggested diversion.

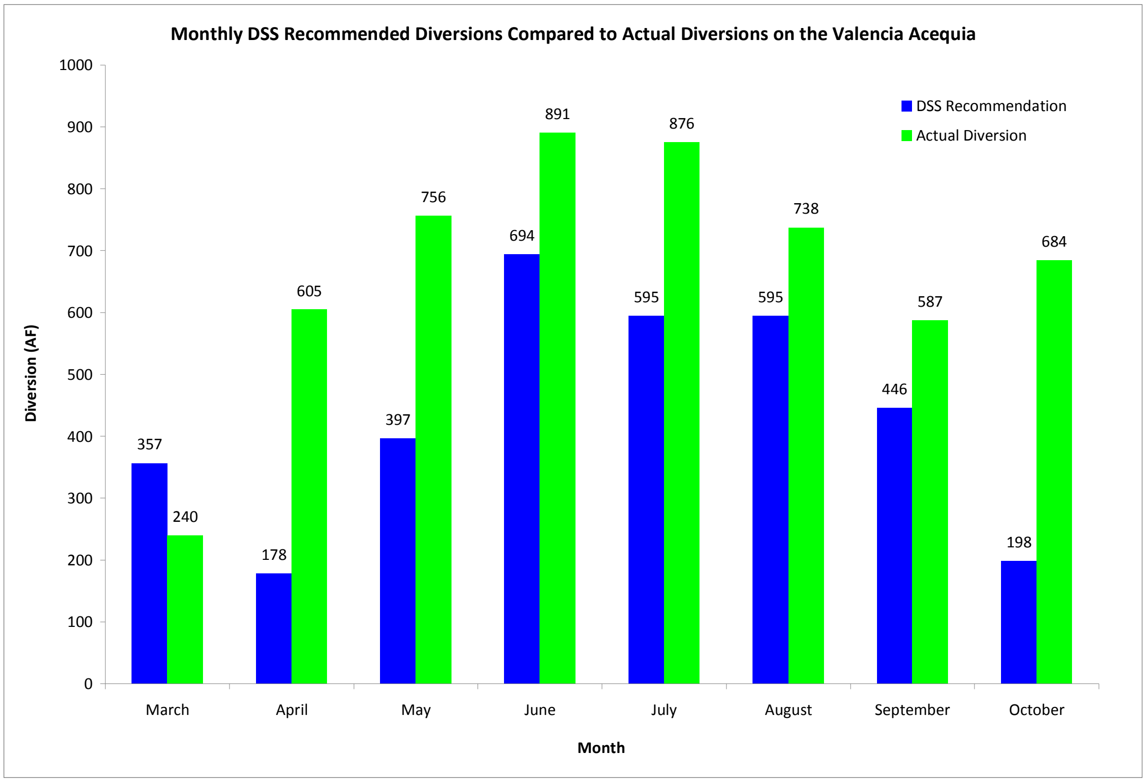


Figure 6.37: Actual Monthly Diversions and DSS Recommended Diversions for the Valencia Acequia in 2009

The mean monthly difference between the actual diversions and the DSS recommended diversions was found to be 269 acre feet. This indicates that on average the ditch-rider and water master were able to match the recommended diversions within 269 acre feet on monthly basis. The comparison of mean monthly diversion does not indicate that the ditch-rider was able to implement scheduled water delivery calculated using the DSS more effectively as the season progressed.

The yearly diversion totals for the Valencia Acequia were also compared to the DSS recommendations. The DSS recommended yearly diversion for the Valencia Acequia in 2009 was 3,460 acre feet. The actual diversion for the Valencia Acequia was 5,377 acre feet. The difference in the yearly actual diversion total and the DSS suggested diversion was found to be 36%. This indicates that the diversion on the Tome Acequia were generally 36% higher than the diversion values recommended by the DSS. Figure 6.38 displays the comparison between the yearly totals for the actual diversion and the DSS suggested diversion. The standard deviation for the DSS monthly values was 188 acre feet and 207 acre feet for the actual diversions indicating minimal variation in the monthly data.

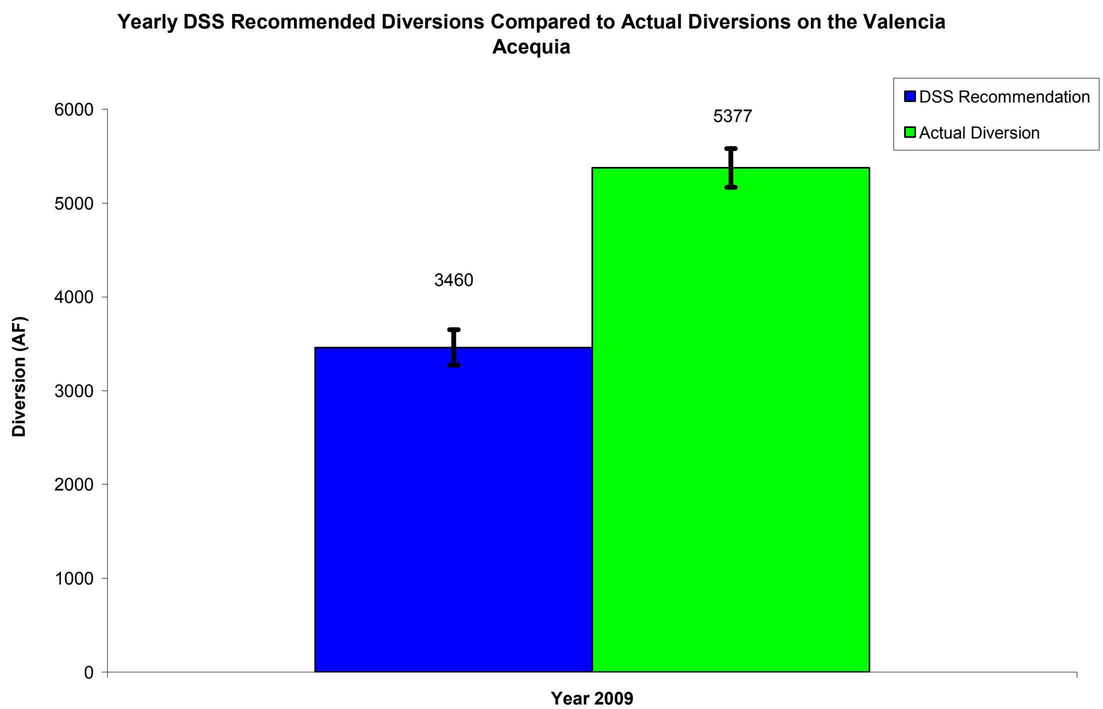


Figure 6.38: Comparison between the Yearly Total for the Actual Diversion and the DSS Suggested Diversion on the Valencia Acequia in 2009

The cumulative actual diversions and DSS suggested diversions in acre feet for the Valencia Acequia were also analyzed. These were analyzed to determine how well the diversions suggested by the DSS were followed as the season progressed. For the Valencia Acequia the actual cumulative diversions were higher than the DSS recommendations. A higher cumulative value as the season progressed indicates that the required amount of water on a cumulative basis was supplied throughout the season and that water users were not negatively impacted by the utilization of the DSS. The Nash Sutcliffe value for the cumulative DSS modeling efficiency was 0.57 indicating that on a cumulative basis throughout the season the ditch-rider was able to follow the DSS recommendations. Figure 6.39 displays the comparison between the cumulative DSS diversion and actual diversion on the Valencia Acequia.

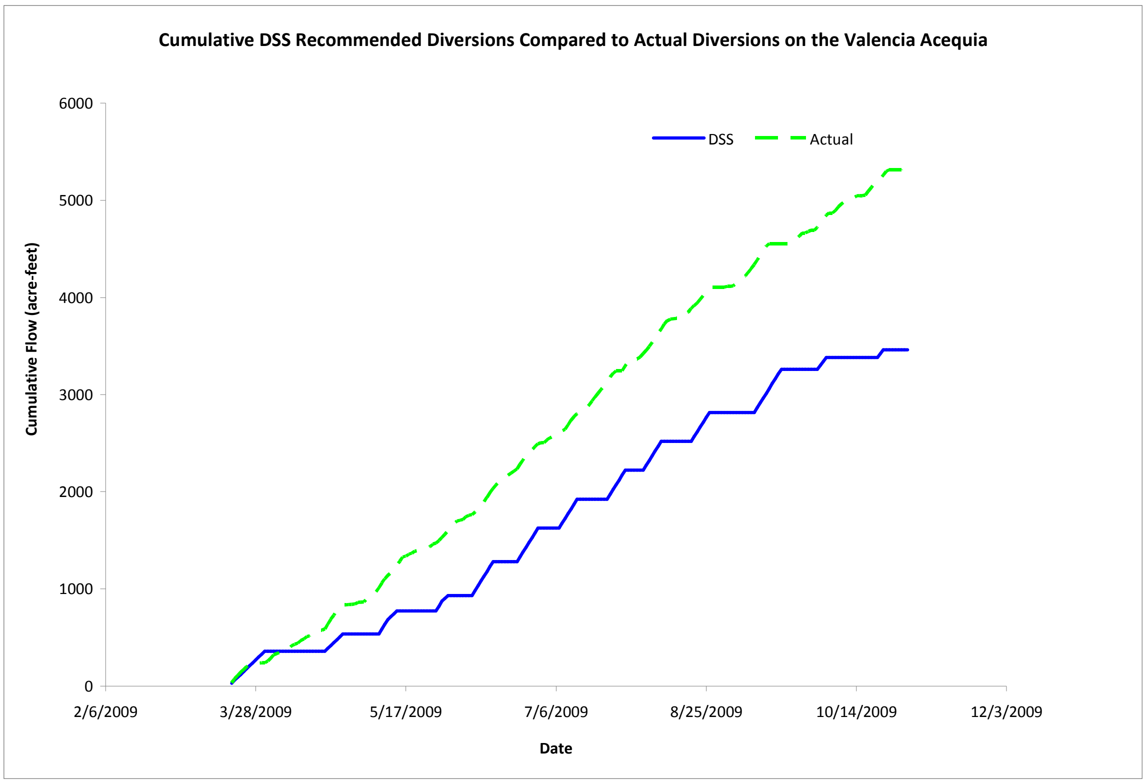


Figure 6.39: Cumulative DSS diversion and Actual Diversion on the Valencia Acequia in 2009

The correlation between the DSS recommended flow and the actual flow utilized during the 2009 irrigation season for the Valencia Acequia was also examined. The correlation coefficient was calculated to be 0.99 which indicates that the actual cumulative daily flow and DSS recommended flow were highly correlated. Plotting the DSS cumulative flow against the actual cumulative flow indicated that the correlation was skewed significantly higher than the ideal fit line which indicates that actual diversions were higher than the DSS suggested diversions. Figure 6.40 displays the correlation between the actual and DSS recommended cumulative flow in acre feet.

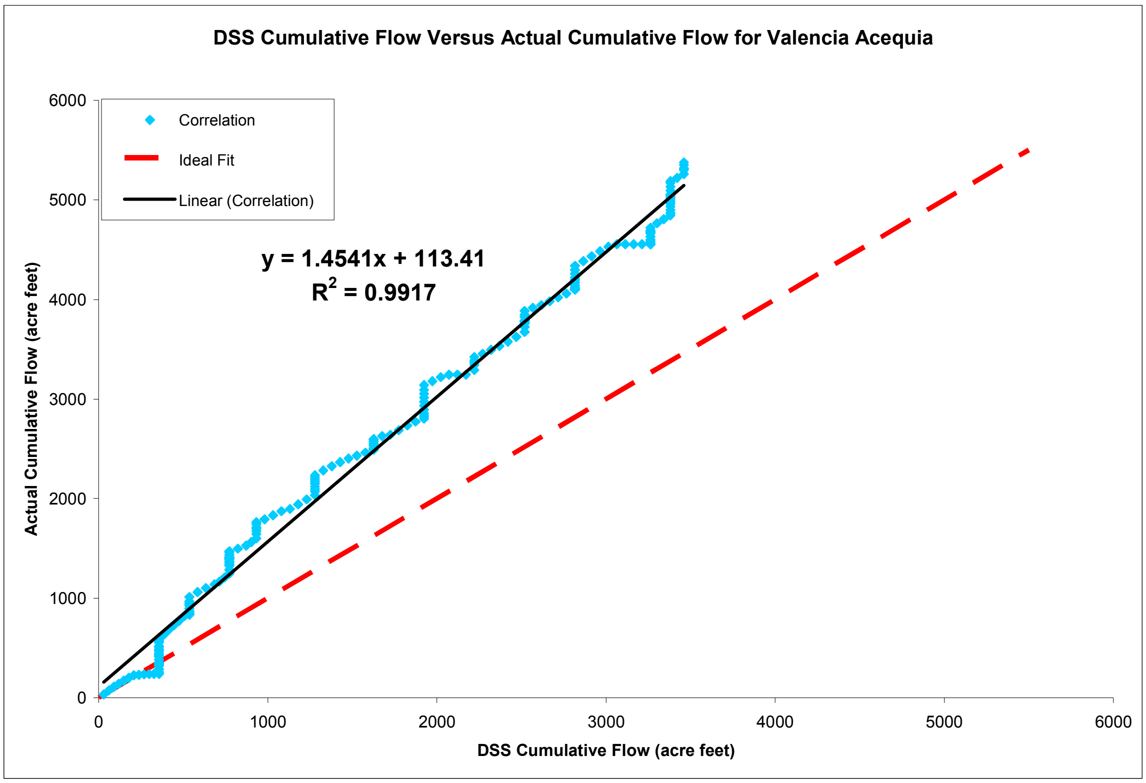


Figure 6.40: Correlation between the Actual and DSS Recommended Cumulative Flow in Acre Feet for the Valencia Acequia in 2009

6.6.9 Overall Diversion Comparison during Implementation

For all six of the canals instrumented with automated Langemann gates the actual diversions were higher than the diversions suggested by the DSS. As the season progressed, the actual diversion numbers more closely represented the DSS recommended diversions. This can be attributed to the MRGCD staff becoming more familiar with the DSS and trusting its recommendations, and ditch-riders consistently scheduling water use. Considering that 2009 season was the first experience with the use the DSS, the results are positive. Although the water master was not able to exactly match the recommended diversion, he was able to keep the actual diversions quite close to the recommendation.

The difference in the yearly diversions varied significantly among the six canals. Figure 6.41 displays the difference in the yearly diversions for the six canals outfitted with Langemann gates.

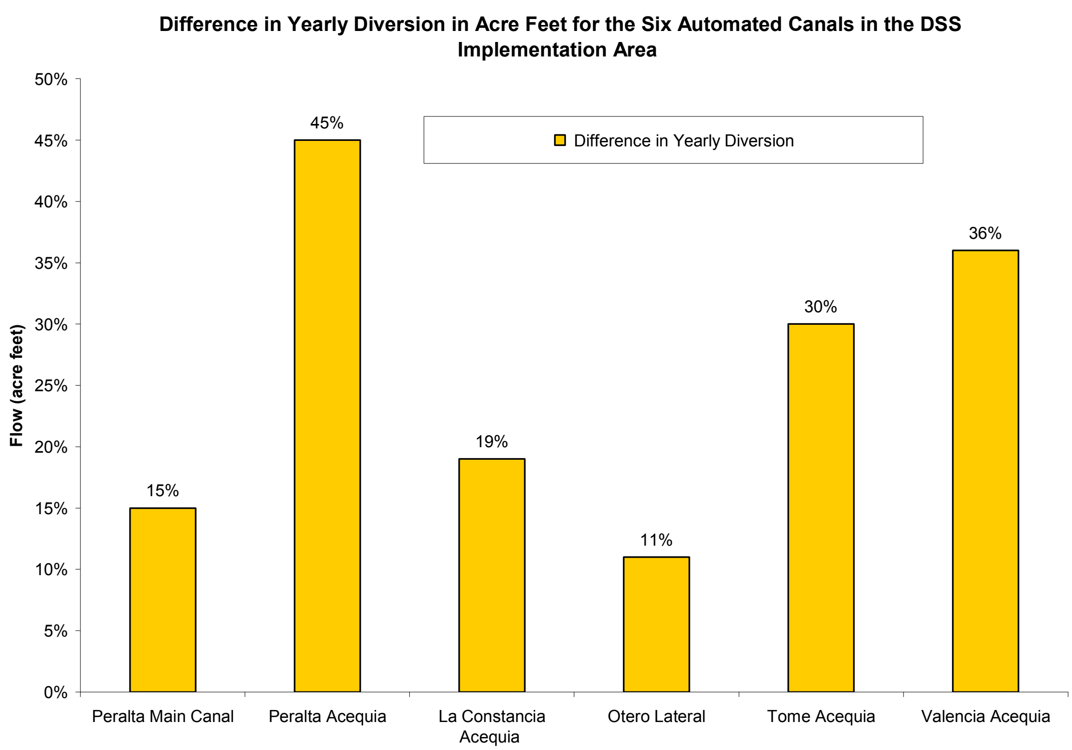


Figure 6.41: Difference in the Yearly Diversion for the Six Canals Outfitted with Langemann Gates

The canals that showed the least difference between the DSS recommended yearly diversion and the actual diversion were the Peralta Main Canal, the La Constancia Acequia and the Otero Lateral. The differences in yearly diversion for these canals were 15%, 19%, and 11% respectively. This indicates that on these canals the DSS recommended flow was followed closely. On the Peralta Acequia the actual flow diverted during the 2009 season was 45% higher than the DSS recommendation. The reason for this difference is that the Peralta Acequia was utilized to route water to the Hell Canyon Lateral when irrigation was occurring on the Isleta Pueblo Indian Reservation. Since the DSS calculates water delivery schedules based on crop demand and not operational constraints this difference is to be expected. On the Valencia Acequia the actual flow diverted during the 2009 season was 36% higher than the DSS recommendation. The reason for this difference is that the Valencia Acequia was also utilized to route water to the Hell Canyon Lateral when irrigation was occurring on the Isleta Pueblo Indian Reservation. The diversion in the Tome Acequia was 30% higher than the DSS suggested diversion. The Tome Acequia was allocated to a new ditch-rider in 2009 and the ditch-rider was not familiar with the service area, water users, necessary water requirements or water delivery practices. Since the ditch-rider was not familiar with the water users and scheduling farmers along an irrigation ditch he often diverted unnecessary water into the Tome Acequia, which flowed directly into the Tome Drain without being utilized by farmers.

Another noteworthy result of implementing the DSS for water delivery scheduling is that the water master was able to significantly reduce the actual water diversions in the Peralta Main Canal during the 2009 irrigation season. During the 2008 irrigation season the yearly total diversion for the Peralta Main Canal was 78,687 acre feet. The total diversion in 2009 of 61,960 acre feet represents a significant reduction of 16,727 acre feet. Although a significant reduction in the diversion was realized, farmers were still provided with adequate water along the Peralta Main Canal. Without the use of the DSS to develop water delivery schedules, the diversion in 2009 would most likely have mimicked the 2008 diversion as the hydrograph and water availability from the Rio Grande were similar in both years. When compared to the four year average from 2005 to 2008 the diversion for the Peralta Main Canal in 2009 is also less. During the period from 2005 through 2008 the average yearly diversion for the Peralta Main Canal was 68,231 acre feet. The diversion for the Peralta Main Canal in 2009 utilizing the DSS is 6,271 acre feet below the previous four year average. The actual diversion during the use of the DSS to implement scheduled water delivery in 2009 could still be greatly improved. 2009 was the first year that the DSS was implemented and many ditch-riders were not familiar with scheduling. This resulted in the actual diversion of 61,960 acre feet being 9,208 acre feet higher than the suggested DSS diversion. With continued implementation and training the actual diversion could be reduced further to match the DSS diversion. Figure 6.42 displays the yearly diversions for the Peralta Main Canal from 2005 through 2009.

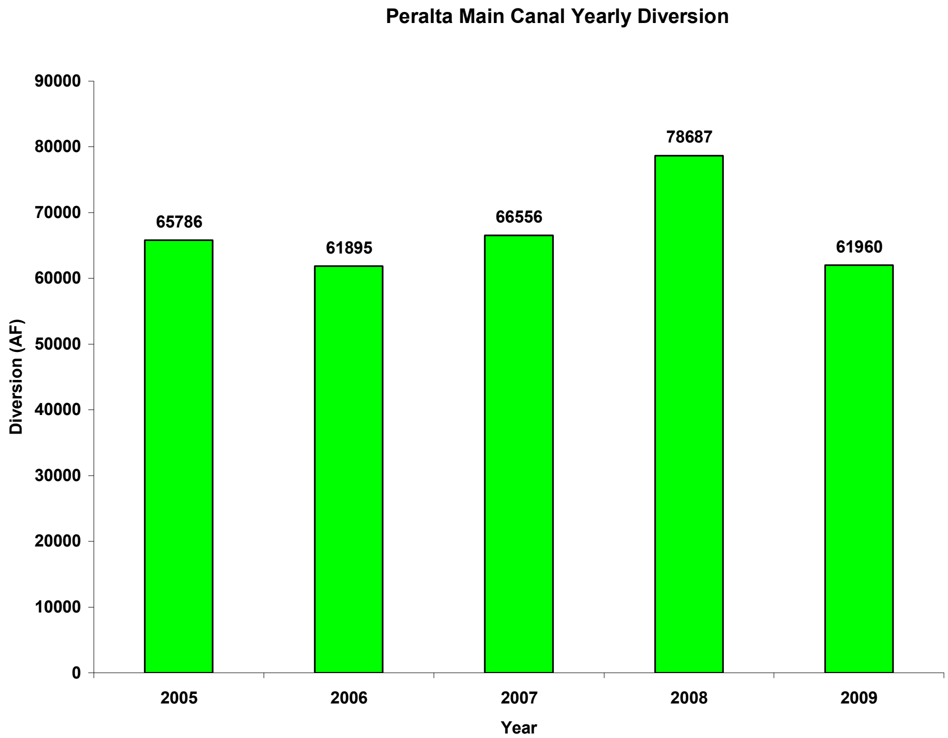


Figure 6.42: Yearly Diversion for the Peralta Main Canal from 2005 through 2009

Using limited scheduled water delivery and infrastructural improvements coupled with SCADA technology, the MRGCD has been able to significantly reduce river diversions. Historically, the MRGCD diverted as much as 600,000 acre feet per year from the Rio Grande. Over the last 3 years, their diversions have averaged less than 352,000 acre feet per year. This is a significant accomplishment as the MRGCD has been able to reduce river head gate diversion to better manage upstream storage, while still providing the needed water to irrigators. Figure 6.43 displays the decreasing trend in total MRGCD river diversions. Currently DSS scheduling is only practiced on the Peralta Main Canal, leaving much room for efficiency improvement. If scheduled water delivery was practiced on all main canals and personnel were trained to effectively implement

DSS schedules an average of 126,900 acre feet could be saved throughout the district. This represents a significant reduction in total diversions of 27%. Overall, the implementation of the DSS verified the premise that a DSS can effectively and equitably be utilized to manage scheduled water delivery operations. A DSS in tandem with infrastructure improvement and SCADA incorporation can significantly reduce river diversion while still serving agricultural demand.

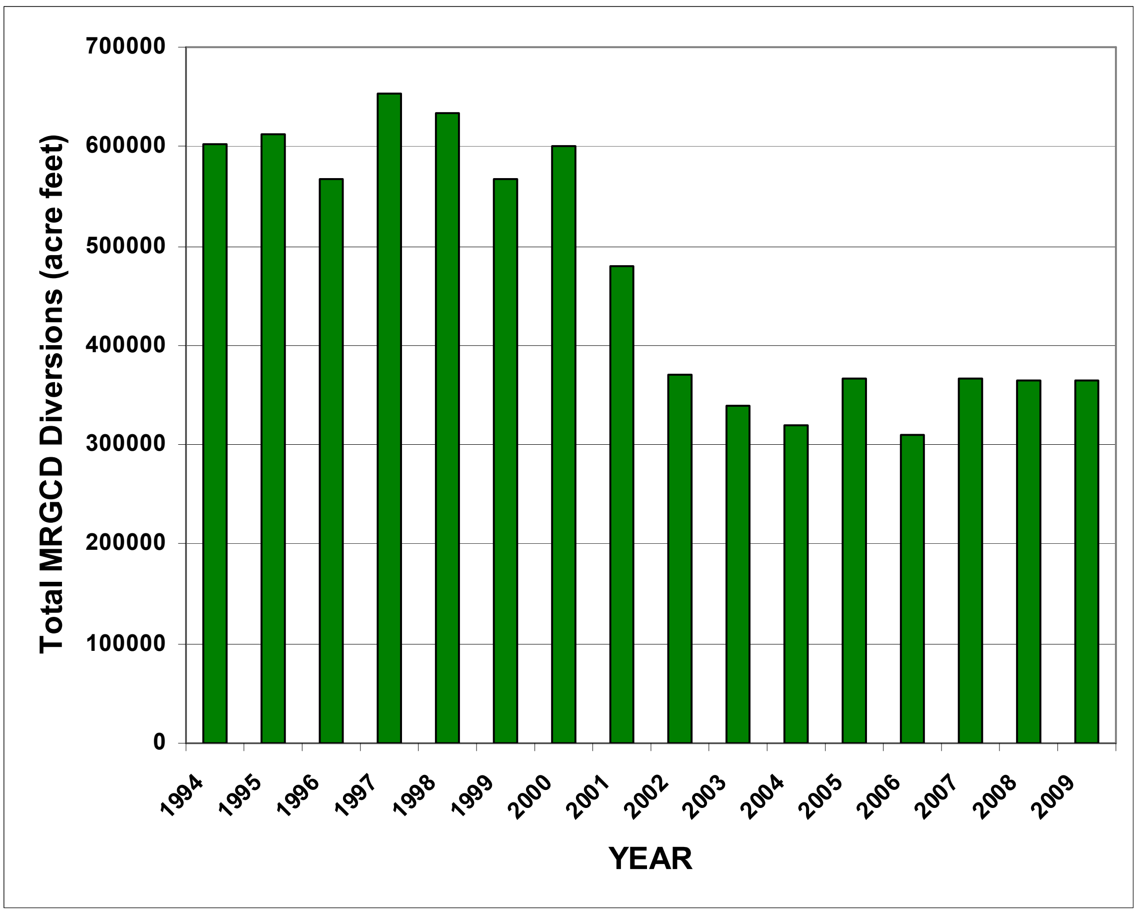


Figure 6.43. MRGCD River Diversions by Year

6.7 BENEFITS OF SCHEDULED WATER DELIVERY TO THE MRGCD

Scheduled water delivery implemented through the use of the DSS coupled with infrastructure modernization and SCADA incorporation has multiple benefits for the MRGCD. These benefits include providing a method for predicting anticipated water use, sustaining efficient agriculture in the valley, meeting flow requirements for environmental concerns and improved reservoir operations. The DSS also provides the MRGCD with a powerful tool to allocate water during periods of drought.

6.7.1 Method of Determining Anticipated Water Use

One of the main benefits that scheduled water delivery using the DSS has for the MRGCD is that the DSS provides a tool to determine anticipated water use. The need for this arises out of the fact that water delivery to farms in the MRGCD is not metered and scheduling is inconsistent. This made it difficult, if not impossible, to place the appropriate amount of water in a canal at the proper time. The MRGCD dealt with this in the past by typically operating all canals at maximum capacity throughout the irrigation season. This provided a high level of convenience for water users, and made the lack of scheduling unimportant. But this practice has had significant negative consequences. Not least of these consequences was the public perception of irrigated agriculture. The MRGCD practice of operating canals at maximum capacity resulted in diversion rates from the Rio Grande that were large.

Through the creation of a thorough and systematic database of cropping patterns, irrigated acreage, automated processing of climate data into ET values, and incorporation of a flow-routing component incorporating the physical characteristics of the MRGCD canals, it became possible to predict how much water users will need. The DSS, with the myriad of calculations it performs, provides the MRGCD water operations manager a method to determine water requirements in advance. The problem of timing and crop stress is thus eliminated, and the MRGCD can operate at reduced diversion levels, while serving its water users.

6.7.2 Sustained Efficient Irrigated Agriculture

Scheduled water delivery implemented through the use of the DSS coupled with infrastructure modernization and SCADA incorporation also has the benefit that it can aid the MRGCD in sustaining irrigated agriculture in the Middle Rio Grande Valley. The agricultural tradition in the Middle Rio Grande Valley dates back over 500 years and one of the main goals of MRGCD is to sustain the agricultural culture, lifestyle and heritage of irrigation. The problem facing the MRGCD over the last ten years has been how to sustain irrigated agriculture amidst drought and increased demands for water from the urban and environmental sectors. These demands for water from other sectors will increase as the population in the Middle Rio Grande Valley grows and expands. Additionally, the MRGCD will be faced with dealing with periodic drought and climate change with the possibility of reduced snow melt runoff in the future. The concept of scheduled water delivery, implemented through the use of the DSS coupled with infrastructure modernization and SCADA incorporation, provides the MRGCD with the ability to sustain irrigated agriculture with reduced river diversions. Scheduled water delivery that is based on crop demand calculated using the DSS and delivered through a highly efficient modernized system will allow the MRGCD to continue supplying farmers with adequate water for irrigation, even though the available water supply may be reduced due to natural or societal constraints.

6.7.3 Meeting Flow Requirements for ESA and Maintaining a Healthy Ecosystem

Scheduled water delivery implemented through the use of the DSS, coupled with infrastructure modernization and SCADA incorporation will also benefit the MRGCD by providing water for environmental purposes. Due to the Endangered Species Act, water operations and river maintenance procedures have been developed in the Middle Rio Grande Valley to ensure the survival and recovery of the Rio Grande silvery minnow. These procedures include timing of flow requirements to initiate spawning and continuous flow throughout the year to provide suitable habitat. Additionally, the entire Rio Grande in the MRGCD has been designated as critical habitat for the RGSM. The concept of scheduled water delivery, implemented through the use of the DSS, coupled with infrastructure modernization and SCADA incorporation, provides the MRGCD with the ability to reduce river diversions at certain times during the irrigation season. Reduced river diversions from the MRGCD main canals may at times leave more water in the Rio Grande for the benefit of the RGSM with credit toward the MRGCD for providing the flow requirements for the recovery of the species.

The DSS may also be useful in providing deliveries of water specifically for the RGSM. Since the listing of the RGSM, the MRGCD canal system has been used to deliver a specific volume of water to points along the Rio Grande to meet flow requirements for the species. At certain times of the year, this is the only efficient way to maintain RGSM flow targets. While not presently incorporated in the DSS, it would be straightforward to specify delivery volumes at specific points in the MRGCD system. These delivery volumes for the RGSM would be scheduled and routed in a similar fashion to agricultural deliveries. Depending on the outcome of the current process of developing RGSM management strategies, this could someday become a very important component and benefit of the DSS.

6.7.4 Benefits to Reservoir Operations

One of the significant benefits of scheduled water delivery in the MRGCD is improved reservoir operations. Traditionally, water demand on a main canal was not calculated and water users did not call for specified reservoir releases as is common in adjudicated basins. The storage reservoirs in the MRGCD are located in the high mountains and it takes up to seven days for released water to reach irrigators. Prior to scheduled water delivery utilizing the DSS, the MRGCD water manager had to guess at what the demand for a main canal would be in advance and then release stored water to meet the assumed demand. Through the use of the DSS and scheduled water delivery the water operations manager can utilize historical climate data to predict what the agricultural demand will be in the future. This allows him to make an accurate calculation of the required release from reservoir storage and minimize superfluous releases.

These reduced reservoir releases have significant benefits for the MRGCD. Since less water is released from storage reservoirs during the irrigation season it allows for increased storage throughout the season. This allows the MRGCD to stretch the limited storage further and minimize the impacts of drought. Decreases in reservoir releases also have the added benefit of providing more carryover storage for the following irrigation season, providing greater certainty for water users in subsequent years.

Larger carryover storage also translates to less empty space to fill during spring runoff. This leads to three benefits for the MRGCD. The first is that reservoirs can still be filled, even in a year when runoff is below average. The second benefit is that in above average runoff years the reservoirs will fill quickly and much of the runoff will go downstream, mimicking the hydrograph before the construction of upstream storage reservoirs. This is a subtle but significant environmental benefit to the Middle Rio Grande and RGSM as peaks in the hydrograph induce spawning, provide river channel equilibrium and affect various other ecosystem processes. The third benefit is that increased runoff will aid the state of New Mexico in meeting Rio Grande compact obligations to Texas. Overall, scheduled water delivery in the MRGCD provides significant benefits to reservoir operations and will allow the MRGCD to reduce reservoir releases, provide more reliable deliveries, increase certainty of full deliveries, and sustain irrigated agriculture.

6.7.5 Use of the DSS in the MRGCD during Drought

Although the implementation of the DSS on the Peralta Main Canal in 2009 proved successful, the DSS will most likely not be utilized to schedule water deliveries in 2010. One of the main reasons for this is that predictions indicate that 2010 will be a full water year and current snow pack conditions are well above average. In times of surplus water the MRGCD will most likely not utilize the DSS for scheduled water delivery because of the associated increase in management intensity and higher operational costs. In drought years the available water supply will be lower and result in tighter and more stringent management requirements to equitably distribute water to users. It is during times of drought and shortage that the DSS will provide the necessary management to distribute water based on crop demand. In the future the DSS will be a powerful tool that the MRGCD can utilize to equitably distribute water and sustain irrigated agriculture through times of low water supply resulting from drought. Through the research and implementation presented in this dissertation the ground work has been laid for the MRGCD to utilize the DSS in times of water shortage.

6.8 WORLDWIDE APPLICATION AND BENEFITS

Scheduled water delivery through the use of a DSS has applications and benefits that can be realized throughout the arid regions of the world. The main benefit of scheduled water delivery utilizing a DSS is that diversions can be reduced in an irrigation system that uses surface application techniques such as furrow and basin irrigation. In the American West urban growth and environmental concerns have forced irrigated agriculture to reduce diversions. In most irrigated systems in the United States that traditionally used surface application, agriculture has opted to improve water use efficiency by changing water application methods to sprinkler and drip irrigation systems. Irrigated agriculture throughout most of the world still relies on surface application and cannot afford to upgrade to systems such as sprinkler or drip irrigation. Therefore, scheduled water delivery utilizing a DSS has the potential to reduce diversions and sustain agriculture.

The DSS and scheduled water delivery also have the potential of meeting future agricultural demands in developing regions throughout the world. As the world population continues to grow there will be an increased demand for food production and in many cases water resources available for agriculture are already fully utilized. Scheduled water delivery utilizing a DSS would allow water users in developing countries with surface application systems to conserve water from their current practices and apply the saved water to increased food production.

The DSS could also be used to refine water delivery scheduling. Many arid regions have been dealing with water shortages for decades and have already implemented scheduled water delivery. In most cases, water delivery schedules are based on a set interval of time and do not coincide with crop demand. In areas where this type of scheduling is practiced the DSS could be used to refine scheduling protocols to include crop demand. Scheduling water deliveries based on crop demands would provide additional saving in areas where scheduled water delivery is already implemented.

The developed DSS could be utilized in any irrigation system worldwide that practices surface irrigation techniques. Through scheduling based on crop demand, overall diversions could be significantly reduced. Reduced diversions could help irrigators deal with drought, and climate change by allowing for increased utilization of stored water. Additionally, reduced diversions could be utilized to grow supplementary crops to supply the needs of a growing population in the future.

CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

Scheduled water delivery has the potential to provide adequate irrigation water while concurrently reducing excess river water diversions. The research presented herein developed a decision support system to calculate water delivery schedules for the Middle Rio Grande Valley. The developed DSS is fully operational and can be used to develop water delivery schedules based on crop demand for every canal service area in the MRGCD. The developed DSS was validated by examining programming logic and through an extensive field study that examined model assumptions. The validation effort verified the hypothesis that a DSS can be used to develop water delivery schedules based on real time crop demands. Through the field study on farm application efficiency, RAM remaining, and canal seepage loss rates in the MRGCD were determined to improve model accuracy. With the data collected during the field study it was possible to describe farmer irrigation practices. The field study also shed light on crop yields in the MRGCD.

Once the DSS was operational it was linked to the MRGCD SCADA network to facilitate scheduled water delivery. During 2009 the DSS was utilized to implement scheduled water delivery in a main canal service area through training of MRGCD staff, a public outreach campaign, and on site support of the DSS. The implementation of scheduled water delivery utilizing the DSS and the MRGCD SCADA network was successful in delivering water to irrigators in a more efficient manner than the traditional practice. The successful use of the DSS to manage water delivery confirmed the premise that a DSS could be implemented for that purpose. Through the use of scheduled water delivery utilizing the developed DSS, the MRGCD will be able to utilize diversions from the Rio Grande more efficiently and sustain agriculture in the Middle Rio Grande Valley. Future use of the DSS will depend on the need for stringent water management and will be directly related to low water supply associated with droughts and future water shortage.

7.2 RECOMMENDATIONS AND FUTURE STUDIES

Through the development and implementation of the DSS scheduled water delivery has been realized in the MRGCD on a limited scale. A future direction would be to continue the implementation of scheduled water delivery using the DSS to include the entire MRGCD. Currently there is no advisory service for irrigators in the MRGCD and developing such a service would provide a significant benefit to the MRGCD. Several other questions regarding accretion in agricultural drains and return flow patterns from applied irrigation water are poorly understood and would provide water managers with useful information and shed light on groundwater and surface interactions in the Middle Rio Grande Valley.

7.2.1 Continued Implementation of Scheduled Water Delivery

The overall goal for the MRGCD in the future should be to continue and expand real-time utilization of the DSS to realize scheduled water delivery on a larger scale. Such an expansion will require multiple years to implement scheduled water delivery supported by the DSS on all main canals in the MRGCD. The first step would be to continue scheduled water delivery practices on the Peralta Main Canal. The next step in expanding scheduled water delivery would be to utilize and implement the DSS to develop water delivery schedules for the Belen Highline Canal, and San Juan Main Canal service areas in the Belen Division. Such an expansion would allow for scheduled water delivery in the entire Belen Division. In order to continue the utilization of the DSS in the Belen Division technical assistance and training of the division water master and ditch-riders will be essential. Continued updating of the DSS water delivery model and its recommendations will be crucial for its acceptance by the water users.

Once scheduled water delivery is implemented in the Belen Division the DSS utilization should be expanded to include the Barr Main Canal and Corrales Main Canal in the Albuquerque Division. The expansion of utilization should be limited to two main canal areas per year as the Albuquerque Division is complex and provides unique challenges to implementing scheduled water delivery. In future years utilization of the DSS on the two remaining main canals, the Albuquerque Main and Arenal Main Canals, in the Albuquerque Division could be accomplished. Following implementation in the Albuquerque Division, the DSS could be used to implement scheduled water delivery in the Socorro Division. Expansion of the DSS and scheduled water delivery to the Cochiti

Division is highly unlikely as the Cochiti Division consists almost entirely of acreage irrigated on Indian Pueblos

The future implementation of the DSS in the Belen, Albuquerque, and Socorro Divisions would consist of a two pronged approach. The first would be linking the DSS and the MRGCD SCADA software to provide real time water delivery recommendations based on crop demand. This would be accomplished by creating data streams and links in the MRGCD SCADA schematics to provide DSS water delivery recommendations. The second would consist of continuous training of MRGCD staff including the water masters and the ditch-riders in topics related to scheduled water delivery and the use of DSS. The public outreach program, to educate water users about the benefits of scheduled water delivery and the use of DSS, is a critical component and should be continued.

7.2.2 Irrigation Advisory Service in the Middle Rio Grande Valley

In most irrigated agriculture systems, water users are not well informed about improving water use and management practices at the farm level. In the Middle Rio Grande, several government and non-government agencies provide agricultural extension services and build water delivery canals, but a service related to the on-farm water management aspects does not exist. Due to the lack of such a service, the MRGCD has the unique opportunity to provide an irrigation advisory service for its water users.

An advisory service would address three inter-related aspects of efficient on-farm water management, which are:

1. When to irrigate?
2. How much water to apply during an irrigation event? And,
3. How to apply water to the lands?

The approach to develop an irrigation advisory service should be focused on four main tasks of developing tools for data acquisition, staff training, dissemination of information, and acceptance and use by the MRGCD water users. Combined, these four tasks form the framework necessary to provide water users in the valley with information related to improved on-farm management practices and efficient water use. The first task would consist of developing tools for acquiring information and data that can assist in the practice of efficient water management practices.

a. One critical piece of information for irrigation water management is the amount of soil moisture available for uptake and use by plants. This information can be acquired by establishing soil moisture monitoring sites on irrigated fields. The data can be linked to the MRGCD website on a real time basis using the already established telemetry network. Providing real time soil moisture information would allow for the precision application of irrigation water resulting in significant water savings. Additionally, a monitoring network would allow managers to ascertain in which areas water is needed the most.

b. Gather climatic data for the Middle Rio Grande valley, compute crop water requirements and make this information available to farmers.

c. Using the DSS computer model and the real-time information of existing soil moisture and crop water requirements, develop advisory irrigation time tables for regions within the MRGCD service area.

The second task would be to formulate and conduct a technical assistance and training program for MRGCD staff. The main objective would be to enhance the technical capabilities of MRGCD staff related to improved on-farm water use and management practices. The third task would disseminate information to MRGCD farmers. The main objective would be to ensure that farmers are aware of the available information, are capable of obtaining it, and are trained on how to utilize the information. By creating an irrigation advisory service the MRGCD could improve water use and management practices on a farm level and further increase water use efficiencies.

7.2.3 Determining Drain Accretions in the Middle Rio Grande Valley

Throughout the 1800's massive overgrazing in the upstream reaches of the Rio Grande watershed resulted in erosion and arroyo cutting which significantly increased the sediment load to the main stem Rio Grande. The sediment influx from the upstream reaches resulted in a 7 foot aggradation of the river bed near Albuquerque. Due to the elevation of the river channel being higher than the surrounding floodplain the Middle Rio Grande between Bernalillo and Socorro can be classified a perched river. The perched nature of the river required the construction of 800 miles of riverside drains to prevent waterlogging, flooding, and leaching of salts in the MRG Valley. During certain time of the year these drains intercept groundwater from the Rio Grande, and during other times of the year they intercept agricultural return flow. The water collected from these drain represents a significant amount of water in the MRG Valley but the drain return flows are currently not incorporated into the Upper Rio Grande Water Operations Model (URGWOM) because the accretion rates and locations of major accretions are poorly understood.

In order to enhance the operational capability of URGWOM, and address return flows in statewide water allocation, a study should be conducted to determine the accretion rates of the riverside drains throughout the entire MRG Valley. Such a study would shed light on localized accretion rates and could also ascertain the source of collected drain flow. A study to determine accretion rates could be conducted utilizing an ADCP and a protocol similar to the protocol presented in Kinzli et al. (2010), which can be found in Appendix E. During such a study the specific conductance of drain water could also be measured to determine the source of drain water.

7.2.4 Quantifying Return Flow Patterns from Applied Irrigation Water

Currently no data exist in the MRG Valley to estimate how much irrigation flow actually becomes return flow. The quantity of return flow on a main canal service area could be determined by measuring flow rates in drains and comparing that flow rate to the inflow rate for the main canal. This approach would basically involve the development of a water balance to calculate return flow. The MRGCD has installed gages on several drains and flow records for these gages could be used to determine the percentage of inflow that becomes return flow. Examining the ratio of return flow to actual inflow will be useful for the DSS because it will refine the user input of return flow percentage. Additionally, observation wells could be placed throughout the valley to monitor how irrigation water returns to drains.

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APPENDIX A: KINZLI AND MYRICK (2009)

BENDWAY WEIRS: COULD THEY CREATE HABITAT FOR THE ENDANGERED RIO GRANDE SILVERY MINNOW

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BENDWAY WEIRS: COULD THEY CREATE HABITAT FOR THE ENDANGERED RIO GRANDE SILVERY MINNOW

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ABSTRACT

Rehabilitation of the Middle Rio Grande in central New Mexico has become necessary to mitigate the effects of over a century of water and land development. The primary driving force behind rehabilitation efforts is the federally endangered Rio Grande silvery minnow (*Hybognathus amarus*). Bendway weirs, erosion control and channel-stabilization structures placed transverse to the channel flow, have been used to prevent river migration while enhancing aquatic habitat. Habitat improvement plans on the Middle Rio Grande include the installation of bendway weirs, but the potential benefits of these structures for Rio Grande silvery minnow are unknown. We conducted a theoretical study on the flow conditions created by bendway weirs to determine if it is possible to create physical habitat for Rio Grande silvery minnow while simultaneously protecting the riverbank. Our study suggested that bendway weir installation could lead to the reduction of downstream displacement of Rio Grande silvery minnow eggs, the creation of Rio Grande silvery minnow feeding and refugia habitat, and the creation of drought or low flow habitat through scour hole formation. We also noted that the weirs could also serve as potential habitat for predators, and suggest further studies to better quantify the possible role of bendway weir installation.

KEY WORDS: Rio Grande silvery minnow; bendway weirs; fish habitats; stream improvement; river rehabilitation,

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INTRODUCTION

Throughout recent history, the demands that humans place on rivers and river systems have increased exponentially (Grigg, 1996). Due to increasing demands, water resources have been over-allocated, and river ecosystems have been permanently altered, often to the detriment of fish and wildlife. The Middle Rio Grande, located in central New Mexico, is a prime example of a river that has been significantly modified by human impacts (Oad *et al*., 2009).

The Middle Rio Grande Valley (Figure 1) runs north to south through central New Mexico from Cochiti Reservoir to the headwaters of Elephant Butte Reservoir, a distance of approximately 282 km (175 mi). The cities of Albuquerque, Rio Rancho and Belen, along with several smaller communities (with a total population of 690 000) are located in or adjacent to the Middle Rio Grande Valley (USCB, 2000). Significant alterations to the hydrology of the Rio Grande began in the 1500s with the arrival of Spanish settlers and continue to this day (Scurlock, 1998). Changes initiated on the Rio Grande through human alteration have had wide-reaching negative effects on the aquatic ecosystem and its fauna, including some of the endemic fishes, such as the Rio Grande silvery minnow (*Hybognathus amarus*).

The decline in native fish species in the Rio Grande has been well documented, and is directly linked to human influences. Historically, there were 27 native fishes in the New Mexico section of the Rio Grande (Cowley, 2006). Currently 45 species of fish are found, yet only 14 native species remain (Cowley, 2006). The Rio Grande silvery minnow is now the only extant pelagic spawning minnow in the river because the Rio Grande shiner (*Notropis jemezanus)* and speckled chub (*Macrhybopsis aestivalis)* have been extirpated (Cowley, 2006), and the bluntnosed shiner (*Notropis simus simus)* and phantom shiner (*Notropis orca)* are extinct (Cowley, 2006).

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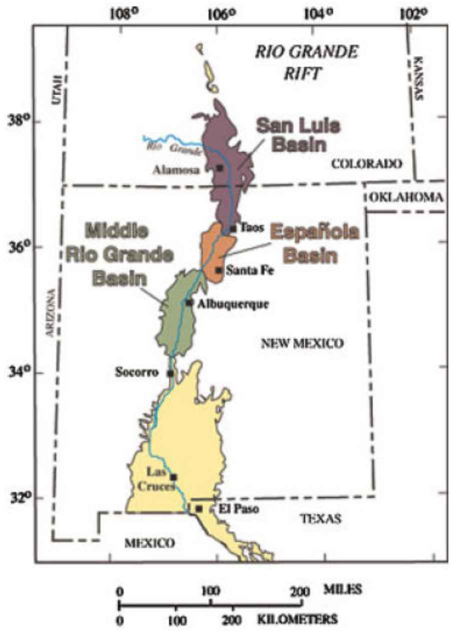

Figure 1. The middle Rio Grande River valley and surrounding basins (USGS, 2008). This figure is available in colour online at www.interscience.wiley.com/journal/rra

Historically the Rio Grande silvery minnow thrived in 3970 km (2465 mi) of rivers in New Mexico and Texas. Today the Rio Grande silvery minnow has been extirpated from 95% of its historical range and it only exists in the Middle Rio Grande between Cochiti Dam and Elephant Butte Reservoir (Propst *et al*., 1987; Bestgen and Platania, 1991; Edwards and Contreras-Balderas, 1991; USFWS, 2003a). Due to the extreme decline of the Rio Grande silvery minnow it was classified as a Federal Endangered Species in 1994 (Federal Register, 2002).

The Rio Grande silvery minnow is one of seven species in the genus ***Hybognathus*** found in the United States (Bestgen and Propst, 1996). The onset of Rio Grande silvery minnow spawning coincides with increased stream flow from spring runoff (Bestgen and Propst, 1996). Spawning involves broadcast fertilization with each female laying between 1000 and 10 000 eggs over a period of 8 h (Bestgen and Propst, 1996). The eggs are semi-buoyant, expand as water is absorbed, and drift downstream in the water column until they hatch 24–48 h later (Bestgen and Propst, 1996; Platania and Altenbach, 1998). Larval and juvenile silvery minnows prefer low velocity habitats (Dudley and Platania, 2007). Low velocity habitats provide areas where drifting algae, organic matter and aquatic organisms collect and provide a critical food source for juvenile Rio Grande silvery minnow (Tetra Tech, 2004). Habitats utilized by adult Rio Grande silvery minnow are mostly areas such as eddies, pools, debris piles, backwaters and side channels (USFWS, 2003a). Rio Grande silvery minnow favour these areas for their low velocity and high rates of primary productivity. Rio Grande silvery minnows prefer to use habitat with moderate depth (15–40 cm) and low water velocity (4–9 cm/s) with silt or sand substrates (Propst *et al*., 1985; Sublette *et al*., 1990; Bestgen and Platania, 1991; Dudley and Platania, 1997; Wetzel and Likens, 2000). Rio Grande silvery minnow prefer mud, silt and sand substrates based on habitat and diet analysis of 1874 specimens (Cowley *et al*., 2006) and are opportunistic omnivores (Magaña, 2007). Shirey (2004) found that Rio Grande silvery minnow feed mainly on diatoms in nutrient-rich areas, along with detritus, pine pollen, cyanobacteria and algae. Larval and adult minnows have similar diets, but it is believed that algae are crucial during early life stages (Tetra Tech, 2004).

Factors linked to the decline of the Rio Grande silvery minnow include habitat modifications, altered flow regimes resulting from dam operations, periodic drying of the river, non-native fishes, hybridization and disruption of egg dispersal (Bestgen *et al*., 1989; Bestgen and Platania, 1990; Bestgen and Platania, 1991; Platania, 1991;

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Cook *et al.*, 1992; Bestgen and Propst, 1996; Platania and Altenbach, 1998; Dudley and Platania, 2007). According to the United States Fish and Wildlife Service, channelization of the Rio Grande and water management have resulted in a large reduction of suitable habitat for the Rio Grande silvery minnow (USFWS, 2003b). Additionally, conversion of the river to a floodway was extremely detrimental to the Rio Grande silvery minnow (Cowley, 2006). Altering river geomorphology to quickly pass floods disconnected the river from the floodplain and reduced the historically braided planform to a single thread channel. Elimination of side channels decreased structural complexity of the river and reduced low velocity habitats available for native fishes (Cowley, 2006). Additional habitat was lost when large woody debris was removed from the river, eliminating snags and debris piles that historically helped create backwater and eddy habitat.

A habitat restoration plan was developed by the Endangered Species Act Collaborative Program (Tetra Tech, 2004) as a template for improving habitat for Rio Grande silvery minnow. The overall goal of the habitat restoration plan is to increase habitat along the Middle Rio Grande and promote completion of Rio Grande silvery minnow life history (Cowley, 2006). Bendway weirs are one proposed habitat restoration option for the Middle Rio Grande. The weirs would be used to stabilize eroding meander bends encroaching on levees and infrastructure while hopefully creating habitat for the Rio Grande silvery minnow

Bendway weirs

Bendway weirs are linear jetty-like rock structures placed on the outside of meander bends protruding into the channel to redirect flow away from the outside bank (Figure 2; Derrick, 1999). The concept of bendway weirs was first conceived by Thomas J. Pokrefke Jr at the US Army Engineer Waterways Experiment Station for use in a physical movable-bed model of a 32 km (20 mi) reach of the Mississippi River (Derrick *et al.*, 1994). Bendway weirs are also referred to as spur dikes, jetties and groynes. Bendway weirs are constructed out of readily available native rock, in most cases the same material that is used for rip-rap. Bendway weirs are constructed of native materials that are easily obtainable; some investigators report that habitat is enhanced when rocks are placed perpendicular to the thalweg (Rapp, 1997). Slack water aquatic habitat is created in eddies formed behind weirs. Additionally, habitat is created when drop-offs form between the main thalweg and depositional areas between weirs. Low flow habitat is also created in the form of a scour hole, located at the tip of a weir; habitat for aquatic invertebrates is created between individual rocks on each weir (Knight and Cooper, 1991). When installed properly, bendway weirs are reported to decrease bank erosion while improving aquatic habitat through the creation of backwater eddies (Shields *et al.*, 1998).

Bendway weirs have numerous ecological benefits to fish, macro and microinvertebrates. Studies show that bendway weirs enhance aquatic habitat by creating pools in unstable streams (Klingeman and Kehe, 1984: Schlosser, 1987). Bendway weirs create and maintain pools, and are reported to be more beneficial to aquatic habitat than traditional measures of bank protection such as rip-rap, jetty jacks, gabions or erosion control blocks (Knight and Cooper, 1991; Hildrew, 1996; Kuhnle *et al.*, 1999; Shields *et al.*, 2000; Kuhnle *et al.*, 2002). Shields *et al.* (1998) documented significant increases in fish density, size, species diversity and overall biomass in an

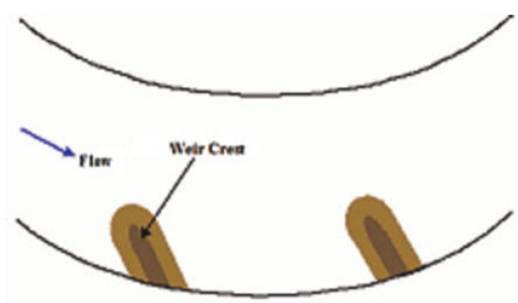

Figure 2. Schematic of bendway weirs placed in a meander bend. This figure is available in colour online at www.interscience.wiley.com/journal/rra

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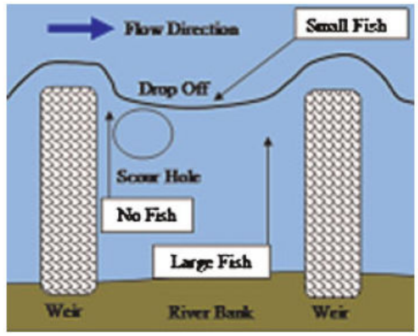

Figure 3. Fish holding locations in bendway weir fields (adapted from Zeidler 1999). This figure is available in colour online at www.interscience.wiley.com/journal/rra

incised stream (Goodwin Creek, Mississippi) following the installation of bendway weirs, concurrent with a 24% increase in stable bank length and the establishment of a bed equilibrium condition after 2 years. Davinroy *et al.* (1998), found that areas on the Mississippi River stabilized with bendway weirs yielded anywhere from 2 to 13 times as many fish compared to similar sites using other types of bank protection. Unique currents produced by bendway weir fields create conditions that attract large numbers of fish (Zeidler, 1999). Observations by sport anglers on the Rhine River, Germany, suggest that weir fields have higher densities of fish than other areas of the river, thus making them popular areas for angling. Anglers have also noted that large colonies of freshwater mussels have attached themselves to the bendway weirs and provide forage for fish. Fish also congregate at drop-offs created by the main current between weirs.

Fish distribution in a bendway weir field has also been reported to be size dependent (Figure 3). Zeidler (1999) reported that large fish and the greatest density of fish in weir fields are found near the toe of the downstream weir (Figure 3). Smaller fish and smaller densities of fish were observed between the two weirs at the drop-off created by the current interface. During normal flow conditions, no fish were observed in the scour hole directly downstream of the upstream weir (Zeidler, 1999). The scour hole created by upstream weirs creates suitable fish habitat during low-flow conditions, but fish favour other locations during normal flow regimes. In 1997, the US Army Corps of Engineers (Keevin *et al.*, 2002) surveyed fish populations in bendway weir fields on the Mississippi River near St. Louis, MO, to test the assumption that fish habitat was improved. The survey recorded 217 fish, double the amount of fish found in a simple meander without bendway weirs (Rapp, 1997; Keevin *et al.*, 2002). Another study conducted on the Mississippi River in 1997 revealed that bendway weir substrate provided better invertebrate habitat compared to a homogenous sand bed substrate (Ecological Specialists Inc., 1997). Both taxonomic richness and diversity were higher at Price's Bend, a bendwith weirs, than at Thompson's bend, a bend without weirs (Ecological Specialists Inc., 1997). The authors contend that since completion of tests in 1997, bendway weirs have become one of the most ecologically beneficial choices in erosion control (Ecological Specialists Inc., 1997).

The studies completed to date highlight some of the ecological and hydraulic benefits of bendway weirs, but they also have some drawbacks. One drawback is the formation of eddies between individual structures that results in unpredictable velocities due to variations in weir length, angle and spacing. Field observations have demonstrated that eddies can cause outer bank degradation and scalloping between weirs and scour at the tip of the weirs (Derrick, 1999). Past and present projects incorporating bendway weirs for bank stabilization have relied mostly on experience and engineering judgment. Lack of design methods for prediction of eddy velocities has resulted in failure of several bendway weir projects (Finley *et al.*, 2001).

METHODS

Through recent research, a design methodology to predict post-installation velocities in bendway weir fields was developed at Colorado State University (Kinzli and Thornton, in press). Four predictive equations were

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developed through laboratory modelling of the Middle Rio Grande (Kinzli and Thornton, in press). The equations allow for the prediction of post-installation velocities in bendway weir fields based on weir design variables such as weir length, weir angle and weir spacing. The four equations allow the prediction of the maximum velocity in eddies, the maximum difference velocity in eddies, the maximum velocity at the toe of bendway weirs and the maximum velocity one foot out from the toe (Kinzli and Thornton, in press). The equations allow the calculation of a velocity ratio that represents to what degree weirs will change velocities from the pre-weir condition. A detailed description of the model study, equation development and design procedure can be found in (Kinzli and Thornton, in press) and in (Kinzli, 2005). These equations allow engineers and fisheries biologists to quantify local and between weir scour and the creation of velocity specific habitat.

The equations are presented here along with a design example that focuses on the Middle Rio Grande. Further detail and clarification can be found in (Kinzli and Thornton, in press).

Maximum Eddy velocity ratio (MEVR)

$$\mathrm{MEVR} = e^{-38.1} \frac{L_{\mathrm{cw}}^{2.32} A_{\mathrm{w}}^{.513} L_{\mathrm{proj,w}}^{14.044}}{L_{\mathrm{proj,cw}}^{15} \nu_{\mathrm{w}}^{2.39} u_{\mathrm{w}}^{*2.39}} \tag{1}$$

where L_{cw} is the length of the weir crest measured along centreline,

A_{w} is the projected weir area, $L_{\mathrm{proj,w}}$ is the projected length of weir to cross section perpendicular to flow and passing through the point at which the centreline and waters edge meet at the design flow, $L_{\mathrm{proj,cw}}$ is the projected length of weir crest to a cross section perpendicular to flow and passing through the point at which the centreline and waters edge meet at the design flow, ν_{w} is the kinematic viscosity and u_{w}^* is the shear velocity with weirs present.

Maximum difference Eddy velocity ratio (MDEVR)

$$\mathrm{MDEVR} = e^{-1.20} \frac{A_{\mathrm{c}}^{.225} L_{\mathrm{arc}}^{.526}}{L_{\mathrm{proj,w}}^{1.502}} \tag{2}$$

where A_{c} is the cross sectional flow area, L_{arc} is the arc length between weirs along design waterline and $L_{\mathrm{proj,w}}$ is the projected length of weir to cross section perpendicular to flow and passing through the point at which the centreline and waters edge meet at the design flow.

Maximum velocity ratio toe (MVR_{Toe})

$$\mathrm{MVR}_{\mathrm{Toe}} = e^{-.475} \frac{L_{\mathrm{proj,cw}}^{.916}}{n_{\mathrm{w}}^{.127} u_{\mathrm{w}}^{*\,.127} L_{\mathrm{proj,w}}^{.8313}} \tag{3}$$

where $L_{\mathrm{proj,cw}}$ is the projected length of weir crest to a cross section perpendicular to flow and passing through the point at which the centreline and waters edge meet at the design flow, n_{w} is the apparent roughness with weirs in place, u_{w}^* is the shear velocity with weirs present and $L_{\mathrm{proj,w}}$ is the projected length of weir to cross section perpendicular to flow and passing through the point at which the centreline and waters edge meet at the design flow.

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Maximum velocity ratio 1 foot (MVR$_{1\ foot}$)

$$\mathrm{MVR}_{1\mathrm{foot}} = e^{-1.72} \frac{L_{\mathrm{proj,cw}}^{.417}}{n_{\mathrm{w}}^{.293} u_{\mathrm{w}}^{*\ .293} L_{\mathrm{proj,w}}^{.2216}} \tag{4}$$

where $L_{\mathrm{proj,cw}}$ is the projected length of weir crest to a cross section perpendicular to flow and passing through the point at which the centreline and waters edge meet at the design flow, n_{w} is the apparent roughness with weirs in place, u_{w}^{*} is the shear velocity with weirs present and $L_{\mathrm{proj,w}}$ is the projected length of weir to cross section perpendicular to flow and passing through the point at which the centreline and waters edge meet at the design flow.

RESULTS

Detailed design example

Consider a meander bend in the Middle Rio Grande that is migrating roughly 2 ft (0.60 m) per year and is threatening adjacent levees, farmland and infrastructure. The meander migration is to be halted using bendway weirs due to habitat concerns for the Rio Grande silvery minnow. The design flow rate for the Middle Rio Grande is 6000 cfs (170 cms) and was chosen because it represents the bankfull discharge of the Rio Grande. The channel through the migrating bend has a bottom width of 140 ft (42.6 m) and can be assumed to have a trapezoidal geometry with side slopes of 3:1 (H/V). Flow depth for the design flow was determined to be 5 ft (1.5 m). Bedslope of the Middle Rio Grande at this location is 0.000863 ft/ft (m/m). River geometry for the design example was determined from GIS data and site visits that were conducted to develop the hydraulic model (Kinzli and Thornton, in press). Weir height was set to 0.5 of the flow depth of the design flow according to guidelines set forth by Lagasse *et al*. (1997). Weirs were assumed to occupy 15% of the channel width in length, angled upstream 60 degrees and spaced using a ratio of 4.1. The slope from the tip of the crest to the toe of the weir was be 1 ft/ft (m/m). Equations 1 and 2 were used to determine eddy velocities after installation and Equations 3 and 4 to determine velocities at the toe and tip of the weirs after installation. *Caution:* although metric units are included in this example only English units should be used to determine the velocity ratios. If metric velocities are needed the final velocities can be converted from English units

Step 1. Establish a design flow rate:

Design flow for the Middle Rio Grande is 6000 cfs (170 cms)

Step 2. Determine the maximum pre-weir centreline velocity:

Flow measurements indicate that the maximum pre-weir velocity at the design flow is 7.7 ft/s (2.3 m/s)

Step 3. Determine the parameters of the design equations:

L_{w} = Length of the weir = 164 ft (49.98 m) × 0.15 = 24.6 ft (7.5 m)
$L_{\mathrm{proj,w}}$ = Length of the weir projected on the perpendicular transect = Cos 30 × 24.6 ft (7.5 m) = 21.3 ft (6.5 m)
L_{cw} = Length of the weir crest = 24.6 ft (7.5 m)−2.5 ft (0.76 m) = 22.1 ft (6.74 m)
$L_{\mathrm{proj,cw}}$ = Cos 30 × 22.1 ft (6.74 m) = 19.14 ft (5.83 m)
A_{w} = Area of the weir = 49 ft^2 (4.55 m^2)
A_{c} = Area of the channel at design flow before weirs = 775 ft^2 (72 m^2)
L_{arc} = Spacing Ratio × $L_{\mathrm{proj,w}}$ = 4.1 × 21.3 ft (6.5 m) = 87.33 ft (26.6 m)
v_{w} = Kinematic viscosity of water at 15.5 C (60 F) = 0.0000122 ft^2/s (.000001134 m^2/s)
P = Wetted perimeter with weirs = 179.14 ft (54.60 m)
R = Hydraulic radius with weirs = A/P = (Ac-Aw)/P = 4.05 ft (1.23 m)
$U_{\mathrm{w}}^{*} = \sqrt{gRS_0}$ = Shear velocity with weirs present = 0.335 ft/s (0.102 m/s)

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n_w = Apparent roughness due to the weir field = 0.0134.

Step 4. Find MEVR using Equation 1:

$$\text{MEVR} = e^{-38.1} \frac{L_{cw}^{2.32} A_w^{.513} L_{proj,w}^{14.044}}{L_{proj,cw}^{15} v_w^{2.39} u_w^{*2.39}}$$

Plug in values

$$\text{MEVR} = e^{-38.1} \frac{(22.1\text{ft})^{2.32}(49\text{ft}^2)^{.513}(21.3\text{ft})^{14.044}}{(19.14\text{ft})^{15}(.0000122\text{ft}^2/\text{s})^{2.39}(.335\text{ft/s})^{2.39}}$$

MEVR = 0.55

Step 5. Find MDEVR using Equation 2:

$$\text{MDEVR} = e^{-1.20} \frac{A_c^{.225} L_{arc}^{.526}}{L_{proj,w}^{1.502}}$$

Plug in values

$$\text{MDEVR} = e^{-1.20} \frac{(775\text{ft}^2)^{.225}(87.34\text{ft})^{.526}}{(21.3\text{ft})^{1.502}}$$

MDEVR = 0.14

Step 5. Find MVR_{Toe} using Equation 3

$$\text{MVR}_{\text{Toe}} = e^{-.475} \frac{L_{proj,cw}^{.916}}{n_w^{.127} u_w^{*\,.127} L_{proj,w}^{.8313}}$$

Plug in values

$$\text{MVR}_{\text{Toe}} = e^{-.475} \frac{(19.14\text{ft})^{.916}}{(.0134)^{.127}(.335\text{ft/s})^{.127}(21.3\text{ft})^{.8313}}$$

MVRToe = 1.45

Step 6. Find $\text{MVR}_{\text{1foot}}$ foot using Equation 4:

$$\text{MVR}_{\text{1foot}} = e^{-1.72} \frac{L_{proj,cw}^{.417}}{n_w^{.293} u_w^{*\,.293} L_{proj,w}^{.2216}}$$

Plug in values

$$\text{MVR}_{\text{1foot}} = e^{-1.72} \frac{(19.14\text{ft})^{.417}}{(.0134)^{.293}(.335\text{ft/s})^{.293}(21.3\text{ft})^{.2216}}$$

MVR1foot = 1.51

Step 7. Establish channel velocities from MEVR, MDEVR, MVR_{Toe} and $\text{MVR}_{\text{1foot}}$

To establish channel velocities after weir installation multiply the found ratio by the pre-weir centreline velocity of 7.7 ft/s (2.35 m/s)

Maximum Eddy Velocity = MEVR × 7.7 ft/s = 0.55 × 7.7 ft/s = 4.23 ft/s (1.29 m/s).
Maximum Difference Eddy Velocity = MDEVR × 7.7 ft/s = 0.14 × 7.7 ft/s = 1.08 ft/s (0.33 m/s).
Maximum Velocity Toe = MVR_{Toe} × 7.7 ft/s = 1.45 × 7.7 ft/s = 11.16 ft/s (3.4 m/s).
Maximum Velocity 1 Foot = $\text{MVR}_{\text{1foot}}$ × 7.7 ft/s = 1.51 × 7.7 ft/s = 11.62 ft/s (3.54 m/s).

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Construction of 15% length weirs, angled upstream by 60 degrees and set at 0.5 of the depth of the 6000 cfs (170 cm) design flow will result in several changes in channel velocity. Pre-weir maximum channel velocity was 7.7 ft/s (2.35 m/s). Maximum eddy velocity and maximum difference eddy velocity with weirs will be 4.23 ft/s (1.29 m/s) and 1.08 ft/s (0.33 m/s) respectively. These velocities represent the maximum velocities that will be found in the eddies. Due to the swirling nature of the created eddies a significant amount of zero velocity habitat will be created. Velocities associated with scour at the tip of the weirs will be higher than the pre-weir velocity of 7.7 ft/s (2.35 m/s). Toe velocity will be 11.16 ft/s (3.4 m/s) and velocity one foot from the toe will be 11.62 ft/s (3.54 m/s). The increased velocities will require a rock size of 14 inch (35 cm) diameter for weir construction using the ASCE rip-rap sizing equation. Fourteen inch diameter rock will provide for weir toe stability at the design flow of 6000 cfs (170 cm).

Bendway weir data collected during Kinzli and Thornton's (in press) laboratory study confirmed the creation of slack water habitat. Using the program Surfer™, velocity plots show that during pre-weir conditions only 2% of the available habitat falls below the 9 cm/s (0.3 ft/s) velocity preferred by the Rio Grande silvery minnow (Figure 4) at bankfull flow conditions. With the installation of bendway weirs low velocity habitat is increased to be 32% of total habitat (Figure 5) for the same flow conditions. Although the weirs in the downstream bend increased the maximum observed velocity due to constriction these velocities did not exceed the 120 cm/s (3.9 ft/s) critical swimming velocity reported for the Rio Grande silvery minnow. These results of the modelling study suggest that the design example would increase low velocity habitat for the meander bend in question by approximately 30%.

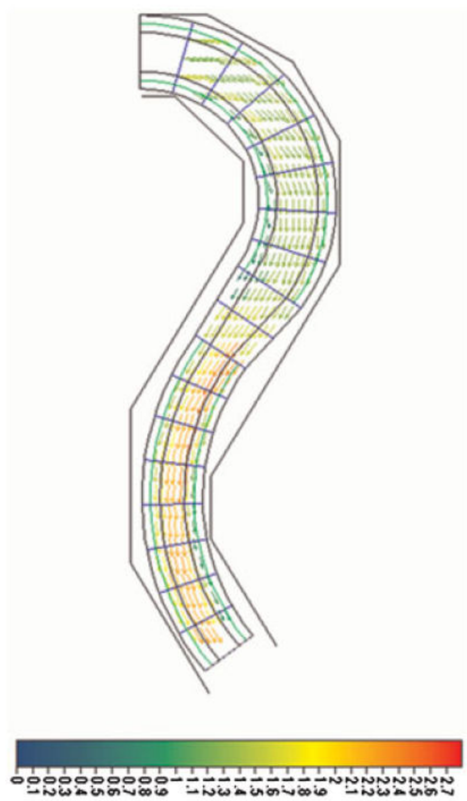

Figure 4. Surfer Plot™ showing velocity (ft/sec) in the model before the installation of bendway weirs. Velocity preferred by the Rio Grande silvery minnow represents only 2% of the available habitat. This figure is available in colour online at www.interscience.wiley.com/journal/rra

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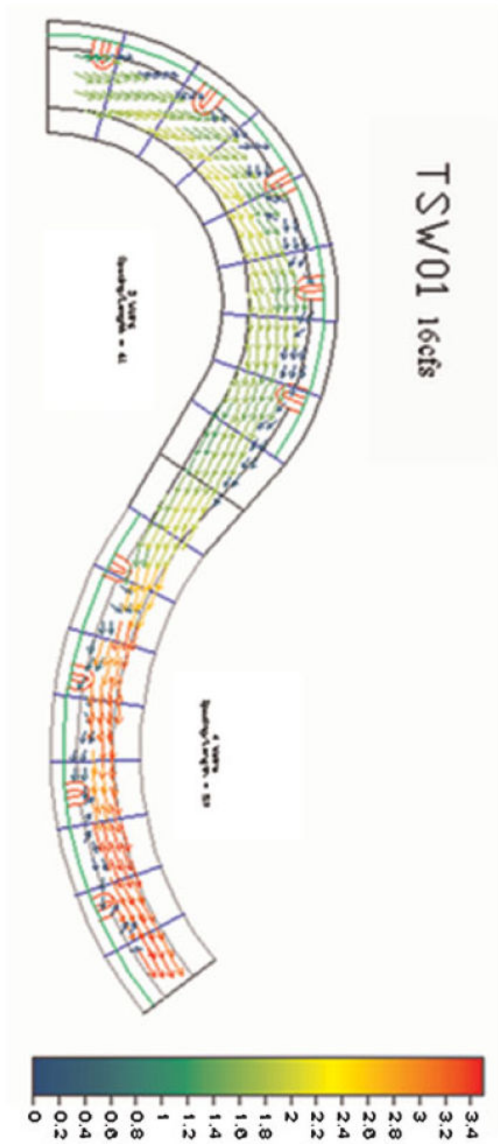

Figure 5. Surfer Plot™ showing velocity (ft/sec) in the model after the installation of bendway weirs. Velocity preferred by the Rio Grande silvery minnow represents 32% of the available habitat. This figure is available in colour online at www.interscience.wiley.com/journal/rra

DISCUSSION

The Middle Rio Grande has become one of the most intensely managed rivers in the United States, having been reduced to a high velocity, single thread channel that does not provide appropriate habitat for Rio Grande silvery minnow (K.R. Bestgen, personal communication). Bendway weirs, if properly designed and installed, are useful tools for several habitat restoration strategies (Tetra Tech, 2004) including;

(1) Establishing channel conditions that reduce downstream egg displacement (Tetra Tech, 2004).
(2) Establishing suitable feeding habitat and cover for juveniles and adults (Tetra Tech, 2004).

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(3) Creating local deepwater habitat that will provide perennially wetted pools during drought (Tetra Tech, 2004; Cowley, 2006).

The following sections address how bendway weirs can be used to achieve the three major habitat restoration goals.

Reducing downstream egg displacement

Increased egg drift into unsuitable habitat such as reservoirs has negative effects for pelagophils (Dudley and Platania, 2007). Pelagic minnows such has the Rio Grande silvery minnow are short-lived species and are threatened by successive reproductive failures from increased egg drift (Dudley and Platania, 2007). In the Middle Rio Grande this is a significant concern because the downstream reach ends in Elephant Butte Reservoir. Bendway weirs could benefit Rio Grande silvery minnow reproduction by reducing the rate of downstream egg drift. Additionally, weirs would increase local egg retention and reduce the effects of habitat fragmentation caused by diversion dams. Studies on the Pecos River on the related plains minnow (***Hybognathus placitus***) demonstrated that young occur mostly in downstream reaches (Hoagstrom and Brooks, 2005) and adults are found in middle and upstream reaches. Using bendway weirs to improve egg retention could allow more juvenile fish to be retained in local stream reaches and perpetuate populations through fragmented habitat reaches. Egg retention in reaches with bendway weirs would be facilitated by increasing channel complexity and providing backwater and eddy habitat. Studies have shown geomorphic complexity of the riverine environments and reduced velocities limit downstream transport of drifting eggs in numerous fish families including Cyprinidae, Catostomidae, Clupeidae, Fundulidae, Poeciliidae and Percidae (Lancaster and Hildrew, 1993; Turner ***et al.*** 1994; Scheidegger and Bain, 1995; Winterbottom ***et al.*** 1997; Reckendorfer ***et al.***, 1999; Bond ***et al.***, 2000). Results from a study on the Pecos River by Medley ***et al.*** (2007) indicate that drifting egg retention is greatest in complex channel reaches (4.5%/km) as compared to 0.6%/km for narrow, deep channelized reaches. In another study, bankline embayments that have a similar geomorphic function to bendway weirs were shown to reduce the downstream drift of artificial eggs (Porter and Massong, 2002). Drifting egg transport on the Rio Grande is 138.7 km during sustained river flows (Dudley and Platania, 2007), which results in eggs travelling as far as Elephant Butte Reservoir. Studies suggest that drifting distance could be reduced through habitat modification by increasing channel complexity (Dudley and Platania, 2007). Bendway weirs would enhance this type of complexity in localized reaches. Reducing downstream egg drift using bendway weirs to increase channel complexity would reduce egg and larval mortality that occurs when eggs are washed into Elephant Butte Reservoir.

Creating feeding and refuge habitat for juveniles and adults

Bendway weirs create habitat for developing eggs, larvae and adults. In channel reaches currently dominated by gravel and cobble substrate, bendway weirs would induce sedimentation of finer particles and create adult Rio Grande silvery minnow habitat. Through sedimentation, sections between weirs would revert from gravel and cobble substrate to a sand and silt bed preferred by the Rio Grande silvery minnow. Large influxes of sediment from tributaries and arroyos would provide the required sediment. In the design example, a section of the Rio Grande lacking weirs with an instream velocity of 2.35 m/s (7.7 ft/s) would result in deposition of particles between 10 and 100 mm diameter. With the presence of weirs that create a maximum difference velocity of 0.33 m (1.08 ft/s), deposition of particles in the 0.1–1 mm size range would be expected. Shoreline habitat would also be increased through the placement of bendway weirs. The nature of bendway weir layouts would greatly increase areas where velocities mimic shoreline habitat along the length of weirs. Platania and Dudley (2003) collected fish along shoreline habitat indicating Rio Grande silvery minnow prefer this type of habitat. Additionally, rock substrate that composes weirs could provide refugia and cover. Based on laboratory experiments, Rio Grande silvery minnow were observed utilizing large substrate such as cobble when it was available (K.R. Bestgen, personal communication), which indicates that rocks used for bendway weir construction could provide structural refugia.

The main benefit bendway weirs would have for the Rio Grande silvery minnow would be the creation of eddies, pools and backwater habitat. The link between Rio Grande silvery minnow and eddy and pool habitat is well documented. In a study of eight cyprinid species on the Pecos River, including the congeneric plains minnow

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(*H. placitus*), cyprinids utilized habitat consisting of backwaters, eddies and slackwaters almost exclusively although it only represented 9% of available habitat (Kehmeier *et al*., 2007). Another study found that Rio Grande silvery minnow use rare habitats such as eddies formed by debris piles, pools and backwaters (Platania and Dudley, 2003). In a study on large woody debris for the New Mexico Interstate Stream Commission it was found that habitats created by large woody debris reduced channel velocities by 26% (SWCA, 2008). It was also found that when Rio Grande silvery minnow were observed they were more abundant at sites with large woody debris (SWCA, 2008). Bendway weirs would significantly increase the amount of eddy and pool habitat by creating eddy habitat between each set of weirs. Additionally, heterogeneity of available habitat would be increased through the placement of weirs.

Through the creation of eddies, bendway weirs would also result in deposition of organic material which provides a food source for the Rio Grande silvery minnow (D. Cowley, personal communication). This has been observed behind snag logs and other slack water areas along the river. Another important benefit that bendway weirs would have is the creation of nursery habitat. The complexity of habitat and structural refugia is important for juveniles (Schlosser, 1991) and is important for the survival of larval life stages of cyprinids in the Rio Grande (Pease *et al*., 2006). This type of habitat is limited in the Middle Rio Grande and the velocity reduction from bendway weirs would increase the amount of nursery habitat available.

Drought habitat creation through scour hole

The use of bendway weirs could also provide refuge habitat in times of drought. Long-term persistence of the species requires perennially wetted habitat (Cowley *et al*., 2003), but the Middle Rio Grande is a perched river and subject to drying. Although a critical minimum flow has been designated for the Rio Grande silvery minnow, sections of the Rio Grande still go dry during drought. The Rio Grande at San Acacia dries during one out of 10 years (MEI, 2002) and substantial portions of the river went dry below San Acacia during 2002 and 2003 (Tetra Tech, 2004). Due to the nature of bendway weir installation, velocities at the tip of the weirs are increased over pre-weir channel velocities. The increased velocities at the tip of the weirs will result in the creation of a scour hole at the tip of each weir. Although no study has been done on the creation of scour holes using weirs it is hypothesized that scour holes will be of substantial size in the sand bed channel of the Rio Grande. Scour holes with substantial depth would provide refugia during drought and reduce the avian predation that is prevalent as the river dries. Additionally, scour holes with significant depth could intercept the groundwater table and allow for pools to persist for a longer period of time. Rio Grande silvery minnow have been shown to utilize scour holes; scour points below large woody debris and diversion dams can be filled with Rio Grande silvery minnow (K.R. Bestgen personnel communication). This suggests that weirs would indeed provide refugia during drought. Additionally, scour points at the tips of weirs would result in the congregation of Rio Grande silvery minnow, creating areas where salvage efforts could be focussed during dewatering events.

Overall benefits

The overall benefit bendway weirs would provide for the Rio Grande silvery minnow is in aiding the completion of its life history in an environment that has been significantly altered from the environment in which the minnow evolved. Promoting completion of the Rio Grande silvery minnow life history has been identified as crucial to the survival of the species (Cowley, 2006) and bendway weirs provide another tool for accomplishing this restoration goal.

Bendway weirs would also be beneficial in the Rio Grande because they exhibit many benefits over other forms of bank protection that are necessary to protect infrastructure and the human population along the river. First, bendway weirs address the goal of channel stabilization and simultaneously create aquatic habitat. Channel stabilization measures such as rip-rap, concrete and concrete blankets, gabions, erosion control fabrics, planted vegetation, Ajacks and reticulated erosion control blocks protect river banks but do not create as much in-channel aquatic habitat (Knight and Cooper, 1991). Second, bendway weirs are less expensive than continuous bank protection such as rip-rap and gabions (Watson, 2003). On the Missouri River bendway weirs deflected flow away from the eroding bank and project costs ranged from US$216 to $244 per foot of bankline, approximately half the cost of traditional designs (Lagrone and Remus, 1998).

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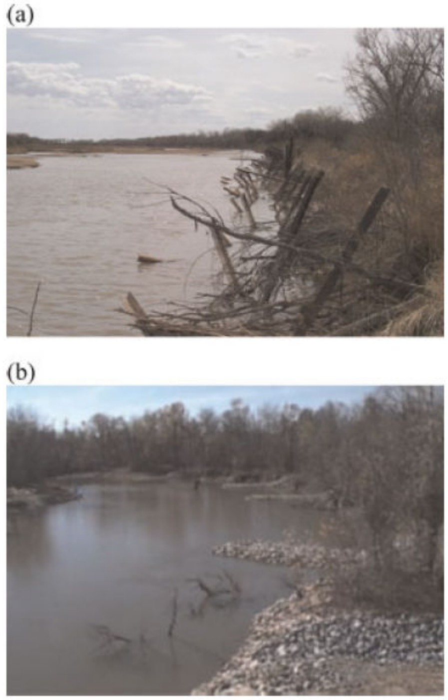
(a)



(b)

Figure 6. (a) Jetty Jacks along the Rio Grande River compared to (b) a bendway weir field (USFWS, 2008; Federal Highway Administration, 2008). This figure is available in colour online at www.interscience.wiley.com/journal/rra

Traditional bank protection measures such as rip-rap and Kellner Jetty Jacks also have the drawback of narrowing the channel, thus preventing overbank flooding (Tetra Tech, 2004). Over 115 000 Kellner Jetty Jacks were installed along the Rio Grande (Figure 6: Lagasse, 1980), and their removal without a suitable bank protection alternative has become impossible due to containment of the floodplain between levees. It is now necessary to prevent migration of the river when it encounters levees and infrastructure due to human interests. Bendway weirs offer a naturalized look (Figure 6) through the use of native rock and are inundated frequently which limits visibility. Bendway weirs would also protect significantly more bankline for a similar number of structures than Jetty Jacks.

Much success in habitat creation has been realized using snag logs that protrude from the bank into the flow. These structures are quite similar to bendway weirs but are limited in application. The relatively small size of the available logs leads to a small positive impact in a large channel; predictive flow and deposition equations are difficult to develop due to the variability in each snag log.

Possible drawbacks

Several questions regarding the use of the bendway weirs remain unanswered. First it remains to be determined if bendway weirs would be a financially feasible option in the Middle Rio Grande Valley. A detailed cost-benefit analysis should be completed wherein the cost of construction and maintenance is compared to the benefits of creating more Rio Grande silvery minnow habitat, and, potentially helping to stabilize the population in the Middle Rio Grande.

Another issue concerning the use of bendway weirs is their longevity. Traditionally bendway weirs have been installed on streams and rivers where the sediment balance is in equilibrium and degrading of the channel bed is

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minimal. The shifting and degrading nature of the current Rio Grande does not resemble an environment where weirs have been used in the past and therefore longevity concerns could arise. This issue could be addressed through a pilot study.

Bendway weirs could also have negative effects on the already highly impacted Rio Grande system. The alteration of channel velocities and sedimentation through the use of weir fields could lead to degradation downstream. The use of weirs could also alter the meander geometry that currently characterizes the Rio Grande planform. By stabilizing one bank, bendway weirs could channelize flow towards the opposite bank which might lead to erosion and a change in planform. The previously mentioned pilot study would also shed light on changes to channel planform. If it is observed that weirs do indeed cause erosion on the opposite channel banks weir angles could be reduced to be perpendicular to the flow (90 degree weirs) to prevent flow alignment towards opposite river banks.

Other concerns with bendway weirs focus on potentially negative effects they could have on the Rio Grande silvery minnow. Large predatory fish may use the eddy currents created by bendway weirs as ambush points from which they could attack unsuspecting minnows and other forage fish. On the Mississippi River, the main species inhabiting bendway weir fields are the gizzard shad (*Dorosoma cepedianum*; a prey species) and the predatory freshwater drum (*Aplodinotus grunniens)* and blue catfish *(Ictalurus furcatus)* (Keevin *et al*., 2002).

The potential predators on the Middle Rio Grande include channel catfish (*I. punctatus*), largemouth bass (*Micropterus salmoides*) and northern pike (*Esox lucius*). It does not appear gizzard shad and freshwater drum actively feed on the Rio Grande silvery minnow (Tetra Tech, 2004), but channel catfish could be a significant predator. Therefore, diet studies in the Middle Rio Grande should be completed to rule out catfish predation as the channel catfish are known to prey on Rio Grande silvery minnow (Tetra Tech, 2004). Northern pike and largemouth bass are ambush predators that should have limited impacts on the silvery minnow because of the turbid conditions in the main river channel.

In order to properly address the possibility of increased predation due to weirs a diet and habitat use study of predatory fish in the Middle Rio Grande should be completed. With data from a diet study it would become possible to determine the primary predators of Rio Grande silvery minnow and address whether these species would feed on minnows congregating in eddies created by bendway weirs. Such a study would also establish if overlap in habitat use does indeed occur. A telemetry study on the possible predators over a realistic range of flow would also indicate whether predators would favour weir fields as habitat.

There are additional factors that affect the Rio Grande silvery minnow in the altered Rio Grande that need to be addressed as part of the restoration process. These include nutrient availability, pollutants and increased salinity, endocrine disruption from wastewater treatment plant effluent, altered temperature regimes, flow pulse timing, food availability, reduced productivity in the Rio Grande and a steep decline in Rio Grande silvery minnow genetic diversity. (Bestgen and Platania, 1991; Cowley *et al*., 2003; Tetra Tech, 2003; Shirey, 2004; Cowley *et al*., 2005; Cowley, 2006; Cowley *et al*., 2006; Dudley and Platania, 2007; Magaña, 2007). Creating velocity-specific habitat by using bendway weirs as an engineered solution only addresses some of the habitat considerations and still represents an artificial solution for a highly-altered system. The above mentioned factors merit further examination to provide a clearer picture of challenges facing the Rio Grande silvery minnow.

CONCLUSIONS

The installation of bendway weirs is a habitat restoration option for the Middle Rio Grande that would stabilize eroding banks threatening infrastructure and concurrently create habitat for the endangered Rio Grande silvery minnow. Past and present projects on other river systems incorporating bendway weirs for bank stabilization and habitat enhancement have relied on experience and engineering judgment. Lack of design methodology for prediction of post-installation velocities has resulted in variable success of bendway weir projects. The four design equations presented here can be used to predict velocities within installed bendway weir fields. Two of the equations can be used to predict eddy velocities behind weirs and two can be used to predict velocities at the toe of weirs. These equations should only be used within the constraints outlined in Kinzli and Thornton (in press). Using the developed design equations, habitat beneficial to the endangered Rio Grande silvery minnow can be created

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while concurrently preventing erosion of levees and infrastructure. Additionally the weirs provide an aesthetically superior alternative to the Kellner Jetty Jacks currently installed along the entire Middle Rio Grande.

Bendway weirs have a demonstrated record in habitat creation; fish communities respond strongly to the placement of weir fields (Rapp, 1997; Davinroy *et al*., 1998; Shields *et al*., 1998; Keevin *et al*., 2002). The number of fish present, along with species diversity, and taxonomic richness is significantly higher in areas with bendway weirs (Ecological Specialists Inc., 1997; Shields *et al*., 1998), and weirs provide more diverse invertebrate habitat compared to the homogenous substrate of a sand bed. Hydroacoustic studies have found that bendway weirs can increase the total abundance of fish in degrading river reaches nearly two-fold (Kasual and Baker, 1996). The unique currents created by weir placement are favoured by fish (Zeidler, 1999) and bendway weirs have been considered by some to be the most ecologically beneficial choice in erosion control (Ecological Specialists Inc., 1997).

If bendway weirs are installed on the Rio Grande the Rio Grande silvery minnow would benefit in three distinct ways. First, weirs would reduce channel velocities in certain areas behind weirs. This would lead to increased egg transport time which should increase survival and maintain minnow populations through segmented river reaches. Second, bendway weirs would create low velocity habitat linked to the survival of the minnow. Currently most sections of the Rio Grande are characterized by a single channel with high velocities and low channel complexity. Weirs would create additional low velocity areas and the channel complexity necessary to maintain rearing and feeding habitat. Additionally, where appropriate, weirs could be installed to initiate the formation of side channels and increase the number of side channels in the river. Third, bendway weirs would provide for scour hole refugia during low flow events ensuring habitat availability during drought.

RECOMMENDATIONS

Before actual implementation of bendway weirs in sections of the Rio Grande can take place several studies should be conducted to field-validate the equations and habitat benefits described in this paper. First, a laboratory study should be conducted to examine the behaviour of Rio Grande silvery minnow in bendway weir fields. Of key importance would be defining how Rio Grande silvery minnow utilize created habitat. A laboratory setting would allow for controlled flow rates, light patterns and would allow for the use of cameras to track the movement and behaviour of Rio Grande silvery minnow in bendway weir fields. Predator introduction into the laboratory system could also be examined. With the introduction of a predator it could be ascertained whether weirs provide cover and refuge habitat or result in increased predation. The installation of bendway weirs in a laboratory setting would also provide the opportunity to examine egg drift and retention within weir fields.

Second, several bendway weir fields could be installed on the Rio Grande as a pilot project. This would allow for field monitoring and observation. Monitoring and observation in the field could consist of presence and absence studies and overall abundance studies. With the installation of bendway weirs on the Rio Grande it would also be possible to perform egg drift studies to determine what percentage of eggs are retained by bendway weirs and to what extent they reduce drifting distance. Egg drift studies could be conducted using gellan beads and the Moore egg collector that has successfully been used on the Rio Grande (Altenbach *et al*., 2000). Egg drift study techniques for small cyprinids in the Pecos River (Medley *et al*., 2007) could be applied to the main stem Rio Grande with weirs installed to determine their effect on egg drift.

In tandem with a monitoring and observation study a predatory diet study should be conducted on the Rio Grande. A study of this nature would involve sampling piscivorous fish that are suspected of preying on the Rio Grande silvery minnow. The diet composition of the predatory fish in the Rio Grande could be determined from stomach analyses. Diet composition analyses would identify predatory fish that are the greatest threat to the Rio Grande silvery minnow and could result in management plans to limit these predatory fish.

Another aspect of bendway weirs that needs to be examined through field experiments is the sedimentation and scour that occurs in weir fields. The equations that were developed were developed under laboratory conditions using a rigid bed and therefore will require field calibration to examine sedimentation patterns. Laboratory tests using a live sand bed and bendway weirs are in progress at Colorado State University (Walker *et al*., 2007). Examining the effects of a varied hydrograph on the function of the weirs would also be a significant contribution of a field study

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To fully implement weirs in the Rio Grande a thorough field evaluation needs to be completed to calibrate the developed equations and validate the ideas set forth in this paper regarding habitat use by the Rio Grande silvery minnow.

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APPENDIX B: OAD, GARCIA, KINZLI, PATTERSON, AND SHAFIKE (2009)

DECISION SUPPORT SYSTEMS FOR EFFICIENT IRRIGATION IN THE MIDDLE RIO GRANDE VALLEY

Decision Support Systems for Efficient Irrigation in the Middle Rio Grande Valley

Ramchand Oad[1]; Luis Garcia[2]; Kristoph-Dietrich Kinzli[3]; Dave Patterson[4]; and Nabil Shafike[5]

Abstract: Water is the lifeblood of the American West and the foundation of its economy, but it remains its scarcest resource. The explosive population growth in western United States, the emerging additional need for water for environmental uses, and the national importance of the domestic food production are driving major conflicts between these competing water uses. The case of the Middle Rio Grande illustrates the problem very well. The river is the ecological backbone of the Chihuahuan Desert region in the western United States, and supports its dynamic and diverse ecology, including the fish and wildlife habitat. The Rio Grande Silvery Minnow is federally listed as an endangered species, and the irrigated agriculture in the Middle Rio Grande has come under increasing pressure to reduce its water consumption and maintain the desired level of service to its water users. This paper will present the writers ongoing research on options to make irrigation system operations more efficient in the Middle Rio Grande Conservancy District (MRGCD). Specifically, it will describe formulation and implementation of a decision support system (DSS) that can assist the MRGCD managers to more efficiently plan and implement their water delivery operations, thereby reducing river diversions. The MRGCD DSS uses linear programming to find an optimum water delivery schedule for canal service areas in the MRGCD irrigation system. The computer model is presently formulated along with the related data sets for two of the four divisions in the MRGCD. For the past 3 years, the model has been validated in the field and the evaluation indicates that the model recommendations are realistic and represent current management practices. The future plans are to complete the data files for the irrigation networks in the remaining two divisions and concurrently help the MRGCD implement the DSS to guide water delivery operation.

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CE Database subject headings: Decision support systems; Irrigation; Scheduling; Water supply.

Introduction

Irrigated agriculture in the western United States has traditionally been the backbone of the rural economy. The climate in the American West with low annual rainfall of 20–38 cm is not conducive to dry land farming. Topography in the west is characterized by the Rocky Mountains which accumulate significant snowfall, and the peaks of the snowmelt hydrograph are stored in reservoirs allowing for irrigation throughout the summer crop growing season. Of the total available surface water irrigated agriculture uses roughly 80–90% (Oad and Kullman 2006).

The combined demands of agriculture, urban, and industrial sectors in the past have left little water for fish and wildlife. As irrigated agriculture uses roughly 80–90% of surface water in the west, it is often targeted to decrease diversions. Due to wildlife concerns and demands from an ever-growing urban population, the pressure for flow reductions on irrigated agriculture increases every year. In order to sustain itself and deal with external pressure for reduced river diversions, irrigated agriculture has to become more efficient in its water consumption. This paper focuses on research regarding improving water delivery operations in the Middle Rio Grande irrigation system through the use of a decision support system (DSS).

Middle Rio Grande Valley

The Middle Rio Grande (MRG) Valley runs north to south through central New Mexico from the Cochiti Reservoir to the headwaters of Elephant Butte Reservoir, a distance of approximately 322 km (Fig. 1). The valley is narrow, with the majority of water use occurring within 8 km on either side of the river. The bosque, or riverside forest of cottonwood and salt cedar, is supported by waters of the Rio Grande and is surrounded by widespread irrigated farming. The Cities of Albuquerque, Rio Rancho, Belen, and several smaller communities are located in and adjacent to the MRG Valley. Although the valley receives less than 25 cm of rainfall annually, it supports a rich and diverse ecosystem of fish and wildlife and is a common outdoor resource for communities in the region. Water supplies available for use in the MRG Valley include: native flow of the Rio Grande and its tributaries, allocated according to the Rio Grande Compact of 1938; the San Juan-Chama project water, obtained via a trans-mountain diversion from the Colorado River system; and groundwater.

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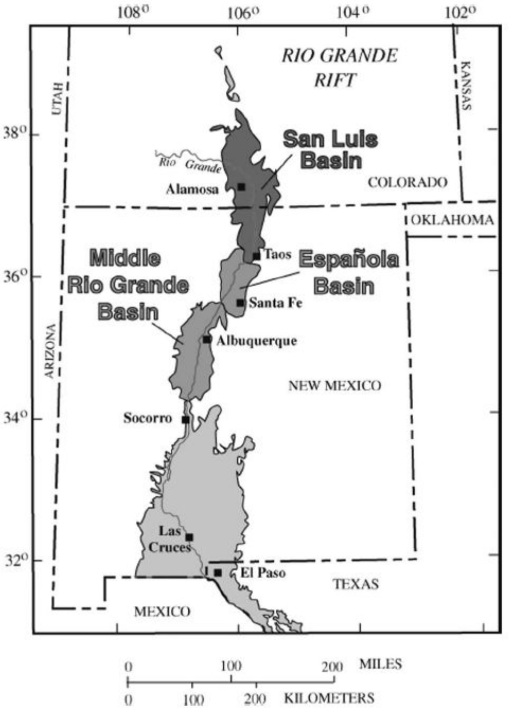

Fig. 1. Middle Rio Grande Valley (Barta 2003). Map courtesy of the U.S. Geological Survey.

Water is fully appropriated in the MRG Valley and its utilization is limited by the Rio Grande Compact, which sets forth a schedule of deliveries of native Rio Grande water from Colorado to New Mexico and from New Mexico to Texas (Rio Grande Compact Commission 1938). Water demand in the MRG Valley includes irrigated agriculture in the Middle Rio Grande Conservancy District (MRGCD) and Indian Lands, and municipal and industrial consumption. In addition to these demands, there are significant consumptive uses associated with the riparian vegetation, reservoir evaporation, and the river flow targets associated with two federally listed endangered species [the Rio Grande silvery minnow (*Hybognathus amarus*), and the southwestern willow fly catcher (*Empidonax traillii extimus*) (USFWS 2003)].

Middle Rio Grande Conservancy District

The MRGCD was formed in 1925 in response to flooding and the deterioration of previously constructed irrigation works (Shah 2001). Water diverted by the MRGCD originates as native flow of the Rio Grande and its tributaries, including the Rio Chama. The MRGCD services irrigators from the Cochiti Reservoir to the northern boundary of the Bosque del Apache National Wildlife Refuge. Irrigation facilities managed by the MRGCD divert water from the river to service agricultural lands, which include small urban parcels and large tracts that produce alfalfa, pasture, corn, and vegetable crops such as the green chile which is famous throughout the southwest. The MRGCD supplies water to its four divisions—Cochiti, Albuquerque, Belen, and Socorro—through Cochiti Dam and Angostura, Isleta, and San Acacia diversion weirs. Water is conveyed in the MRGCD by gravity flow through primarily earthen ditches. On-farm water management is entirely the responsibility of water users and application is typically surface (flood) irrigation, either basin or furrow. The MRGCD does not meter individual farm turnouts, and ditch riders estimate water delivery on the basis of time required for irrigation.

During recent drought years, low flows combined with streamflow requirements for the endangered Rio Grande Silvery Minnow have drastically reduced available water supplies. In order to deal with reduced water availability, the MRGCD has taken a proactive approach to be a more efficient water user and service its irrigators with reduced river diversions. Toward this end, the division managers and ditch riders are increasingly practicing scheduled water delivery, which is an effective way to fulfill demand with reduced available water. Scheduling in the MRGCD is currently done without tools and is based on tradition and other noncrop demand-related variables. This scheduling protocol can be greatly enhanced through the use of a DSS to allow for demand driven scheduling.

Scheduled water delivery (SWD) is used in irrigation systems worldwide to improve water delivery and to support water conservation. In SWD, lateral canals receive water from the main canal based on their crop water requirements, allowing water use in some laterals when others are closed. In addition to this water scheduling among laterals, there can be scheduling within laterals whereby water use is distributed in turns among farm turnouts along a lateral. By distributing water among users in a systematic scheduled fashion, an irrigation district can increase water use efficiency, decrease water diversions, and still meet crop water use requirements, without shortchanging irrigators.

Decision Support Modeling of Irrigation Systems

The New Mexico Interstate Stream Commission and the MRGCD have sponsored a research project with Colorado State University to develop a DSS, to model and assist implementation of scheduled water delivery in the MRGCD's service area. A DSS is a logical arrangement of information including engineering models, field data, GIS, and graphical user interfaces, and is used by managers to make informed decisions. In irrigation systems, a DSS can organize information about water demand in the service area and then schedule available water supplies to efficiently fulfill the demand.

The conceptual problem addressed by a DSS for an irrigation system, then, is how best to route water supply in a main canal to its laterals to best meet predicted or scheduled demand, when minimizing required diversions from the river. The desirable solution to this problem should be "demand driven," in the sense that it should be based on a realistic estimation of water demand. The water demand in a lateral canal service area, or for an irrigated parcel, can be predicted throughout the season by evaluating crop water requirements based on information on the irrigated area, crop type, and soil characteristics. The important demand concepts are: when is water needed for an irrigation (irrigation timing), for how long is the water needed during an irrigation event (irrigation duration), and how often must irrigation events occur for a given service area (irrigation interval).

DSS have found implementation throughout the American West and are mostly used to regulate river flow. DSS on the river level are linked to gauging stations and are used to administer water rights at diversions points. Although DSS have proved their worth in river management, few have been implemented for modeling irrigation canals and laterals (Oad et al. 2006). The research presented in this paper has focused on developing, calibrating, validating, and eventually implementing a DSS capable of modeling flow on a main canal and its laterals, with the overall goal of efficient irrigation water delivery.

Formulation of Decision Support System for the Middle Rio Grande

Model Programming

The model programming uses an objective function to schedule water deliveries to lateral service areas [Eq. (1)]. Constraints on variables within the objective function are specified and must be satisfied in determining the optimum solution. This process achieves the result that water delivery to laterals with more immediate crop water needs is favored, and delivery to laterals that have sufficient water in a given time step is minimized

$$\text{Minimize } Z = \text{MP}_{D\text{-}0}X_{D\text{-}0} + \text{MP}_{D\text{-}1}X_{D\text{-}1} + \text{MP}_{D\text{-}2}X_{D\text{-}2} + \text{MP}_{D\text{-}3}X_{D\text{-}3} \quad (1)$$

where Z=sum of a modified priority (MP) multiplied by amount of supply (X) from the dummy supply to each demand node. The subscripts refer to the nodal points between which flow occurs, i.e., X_{D-1} refers to flow from the dummy supply to Check 1, and MP_{D-1} refers to the modified priority of demand to be satisfied at Check 1 from the dummy supply node (Fig. 2). The MP value reflects the need-based ranking system where demand nodes with lower soil moisture are favored for irrigation. The modified priority is calculated by: (1) counting the days until the readily available soil moisture for a given demand is depleted; (2) examining when the last rotation occurred; and (3) examining whether laterals belong to the same main canal that is being irrigated. Counting the days until dry represents the soil moisture that remains for crop consumption and the relative need for an irrigation event. Examining the last irrigation occurrence prevents laterals that have already received water from receiving water again until irrigation demands are met for all laterals. The idea behind this is that all laterals should get a scheduled irrigation event before a lateral receives water for a second time. Analyzing if canals belong to the same main canal service area is done to minimize the conveyance losses and therefore favors irrigating one main canal service area completely before water is shifted to another service area. MP values for the DSS range from 1 to 10,000. Lower values indicate a higher need for irrigation with 1 representing a lateral service area where the entire readily available moisture (RAM) is depleted, and 10,000 representing a lateral where the RAM is entirely filled. The objective function is solved in conjunction with a system of mass balance equations (Table 1) representing the actual water (and dummy water) delivered to demand nodes, along with other physically based constraints.

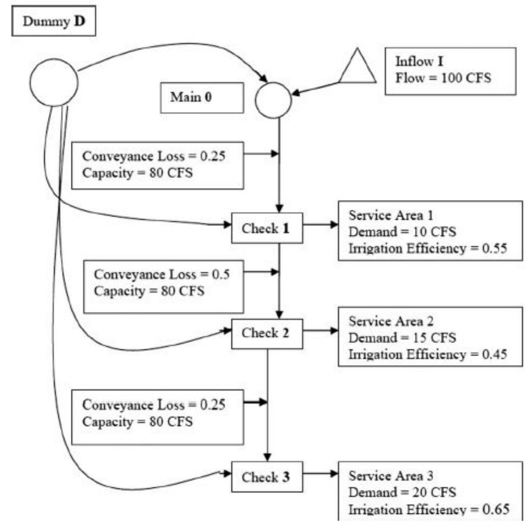

Fig. 2. Schematic of model programming

The variables in the objective function represent the links in the network between the dummy supply and the demand nodes. The coefficient of each variable represents the flow "cost" of that link. In other words, delivery of water to a node without a need for water results in a higher cost. The ranking system has been assigned such that minimization of this objective function will result in minimization of water delivery to demand nodes that already have sufficient water.

Constraints on the solution of the objective function express the mass balance relationships throughout the link-node network and the capacity limits on flow (Table 1). A mass-balance constraint is created for each node that establishes the inflow and outflow to that node. The coefficients of the variables for each constraint are represented as a matrix, with a column for every variable in the objective function and a row for every node. Inflows are indicated by negative values, and outflows are positive values. Outflow coefficients are always one, and inflow coefficients are the conveyance loss of the connection. The objective function is subject to the following constraints (Hillier and Lieberman 1995):

Table 1. Constraints for DSS Objective Function

	Flow from $I\to 0$	Flow from $0\to 1$	Flow from $1\to 2$	Flow from $2\to 3$	Flow from $D\to 0$	Flow from $D\to 1$	Flow from $D\to 2$	Flow from $D\to 3$	Constraint
Inflow	X_{1-0}								$<=I$
Check 0	$-X_{1-0}$	$+X_{0-1}$			$-X_{D-0}$				$=R_0$
Check 1		$-L_1X_{0-1}$	$+X_{1-2}$			$-X_{D-1}$			$=R_1$
Check 2			$-L_2X_{1-2}$	$+X_{2-3}$			$-X_{D-2}$		$=R_2$
Check 3				$-L_3X_{2-3}$				$-X_{D-3}$	$=R_3$
Dummy						X_{D-1}	$+X_{D-2}$	$+X_{D-3}$	$<\infty$

where $X_{0-1} <= C_{0-1}$; $X_{1-2} <= C_{1-2}$; $X_{2-3} <= C_{2-3}$. All $X_{i-j} >= 0$. The variables used are as follows: I=total available inflow flow; X_{i-j}=flow in a canal reach between points i and j, C_{i-j}=maximum capacity of the canal reach between points i and j; D refers to a dummy supply node that is used to force the demands and supplies to balance, the subscript 0 refers to the inflow node, and subscripts 1, 2, 3,…refer to nodal points, typically located at check structures; L_{i-j}=conveyance loss between in the canal reach between points i and j; and R=demand (water requirement) at the nodal point indicated by the subscript (can be zero if not associated with a lateral diversion point).

For example, the third row refers to activity at check 1. There is an inflow from the headgate ($-L_1X_{0-1}$), and it is given a negative sign as by convention all inflows are negative. The conveyance loss is represented by the coefficient L_1. There is an outflow to check 2 ($+X_{1-2}$) (positive sign, as by convention all outflows are positive). To ensure that the system balances, there is also an inflow from the dummy source ($-X_{D-1}$). Because this node represents a demand, the solution for this row is constrained to be exactly the demand (R_1). If a node represented a source, then the solution for the row would be constrained to fall between zero and the inflow, which allows the use of less than the total amount of water available if the demands are less than the supplies or if at some point in the network the capacity is insufficient to route the inflow. The first row in the constraint equations represents this type of node.

A conveyance loss factor is input to the supply network module as a fractional value of flow per mile. The conveyance loss (L) to be applied in the mass balance equation, reflected in the constraints, is calculated by subtracting the fractional value from one and raising it to the number of miles of the canal segment between nodes. For example, a 3 mi reach with a 0.015 conveyance loss factor would have a loss of $1-(0.985)^3=0.0443$ of the instream flow to this reach.

The ranking system used to derive the MP values for the objective function is a two-step process, involving assignment of a priority (P) based on the irrigation need at demand nodes, and then, a modified priority that effectively reverses the ranking so that nodes with the least need are the preferred recipient for dummy water. This results in the actual available water being delivered to the demand nodes with highest irrigation needs.

First, a priority (P) is assigned to each of the demand nodes, with smaller values indicating higher needs for irrigation. The priority is based on the number of days until the service area runs out of RAM. If the service area is not being irrigated, 100 is added to the priority, which forces the system to favor areas being irrigated until the RAM is full again. The concept of a subsystem was also added to give priority to remaining canals within a group on the assumption that if one of the canal service areas in the subsystem is being irrigated, it would be desirable that the remaining canal services areas in the same group be irrigated as well. If a service area is determined to be in a subsystem that is being irrigated, its priority is set to 50 plus the number of days to depletion of the RAM. This makes it a higher priority than other services areas not in the subsystem and, therefore, the optimization program will try to water them first.

Normally a service area is irrigated only once during a rotation, but in situations when excess water is available, service areas that are in need of water are added back into the scheduling algorithm with a priority equal to 500 plus the number of days to depletion of RAM.

The ranking system is implemented by modifying the priorities with respect to the dummy connections, effectively reversing the priorities. Currently the MP for the "dummy -> node x" connection is $100{,}000/P_x$. For example, if the node has a priority of 105, then the priority assigned to the connection is 100,000/105 or 952.38. This will force dummy water to be delivered first to the lower priority nodes, leaving real water for the high priority nodes. The MP values are represented by the MP variables in the objective function. The linear programming software utilized in the DSS is a package called glpk (GNU Linear Programming Kit). The software and documentation can be downloaded from http://www.gnu.org/software/glpk/glpk.html.

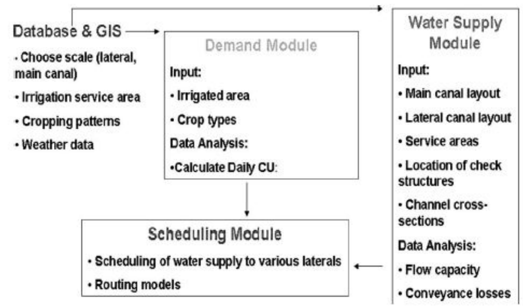

Fig. 3. Model structure displaying the three modules

Model Structure

The DSS consists of three elements; a water demand module, a supply network module, and a scheduling module (Fig. 3). A graphical user interface (GUI) is the framework for linking the three elements of the DSS, and provides the user with the ability to access data and output for the system. The project GIS and databases are used to develop input for both the water demand and the supply network modules. The databases in the model consist of several Access databases that can be populated from various sources. Some of the input is directly linked through the GUI and some is handled externally through the database in this DSS version.

Water Demand Module

The water demand module of the MRGCD DSS can be implemented using either the ET Toolbox developed for the Middle Rio Grande Valley by the USBR (http://www.usbr.gov/pmts/rivers/awards/Nm2/riogrande.html) or the integrated decision support consumptive use, or IDSCU model, a model developed over a period of years at the Colorado State University (http://www.ids.colostate.edu/projects/idscu). The ET Toolbox calculates the crop irrigation requirement (CIR) throughout the valley for a variety of agricultural crops using data from weather stations and remote sensing. The IDSCU model consists of a GUI written in Visual C++ and program calculations implemented with FORTRAN. The IDSCU model offers numerous features and options and calculates the following: crop consumptive use, CIR, and RAM as a capacity. The latter two variables, CIR and RAM, are subsequently used in the supply network module. Crop consumptive use using IDSCU is calculated using the Penman–Montieth method. The reference ET is calculated using weather data from the MRGCD. Crop coefficients using growing degree days are applied to the Penman-based ET to obtain a consumptive use for each crop type throughout the growing season. The water demand module performs these calculations to obtain a spatially averaged consumptive use at the lateral service area level, using the distribution of crop types within each service area. The data for the crop distribution in each lateral service area are obtained from the MRGCD ditch-rider logbooks.

The CIR using IDSCU is calculated by accounting for the effective precipitation using the soil conservation service method. The crop irrigation requirement is calculated on a daily basis, corresponding to the water needed to directly satisfy crop needs for all acres in the service area. If the ET Toolbox is used to populate the water demand module the CIR is directly taken from the ET Toolbox database. The crop irrigation requirement for the service area is subsequently passed to the supply network module, where it is divided by an efficiency factor to obtain a lateral service area delivery requirement.

Based on acreages, crop types, and soil types within each lateral service area, a RAM is calculated. The RAM calculated in this context represents a storage capacity to be filled and depleted over several irrigation cycles during the course of the irrigation season. During each irrigation, it is expected that an amount of water equal to the RAM will be stored in soils which is then depleted due to crop water use.

Supply Network Module

The supply network module represents the layout of the conveyance system, its physical properties, supply to the conveyance network, and the relative location of diversions from the network to the lateral service area. The layout of the conveyance system is specified through a user-designed link-node network. Through the DSS GUI, a user can drag and drop different types of nodes such as inflows, demands, and return flow nodes. The link-node network represents the connections between canals or laterals and demands for water at each service area.

Irrigation Scheduling Module

The irrigation scheduling module can be used to plan water deliveries to meet crop demand at the lateral and at the main canal level. The module calculates and displays a schedule for the laterals on a given main canal. This schedule indicates how many laterals can be run at a time, how long each lateral should run, and how often. The module is currently set up to run on a daily time step. This module calculates the daily irrigation schedule using mass balance equations and the linear programming solver. The approach is based on the consideration that the farm soil root zone is a reservoir for water storage, for which irrigation applications are inflows and CIR is an outflow.

Model Field Testing and Calibration

Data Collection and Calibration

Data files were initially developed for each main canal and its laterals by collecting information related to cropped acreage and type, soil types, and the lateral service area. The water holding capacity of the soil in each lateral service area was determined using GIS and NRCS (natural resources conservation service—www.nrcs.usda.gov) soil maps. The NRCS soil maps used are of Sandoval, Bernalillo, Valencia, and Soccoro Counties in New Mexico. System infrastructure data were also collected to ensure accurate representation of the distribution network. Canal capacity measurements were made to represent actual canal carrying capacities in the DSS. To calibrate the model, a sensitivity analysis was performed on the main input variables of application efficiency, conveyance loss, and RAM remaining before irrigation occurs. Sensitivity analysis consisted of varying one single variable and keeping all other variables constant. Using the sensitivity analysis the model input parameters were calibrated and found to be an application efficiency of 50%, a conveyance loss of 1.5%/mil, and a RAM (readily available moisture) remaining before irrigation occurred of 0%.

Table 2. Comparison between the DSS and Actual Practice for Mean Irrigation Duration, Mean Irrigation Interval, and Mean Irrigation Flow Rate

Year	Mean DSS recommendation	Mean ditch-rider practice	Difference
Irrigation duration (days)			
2004 (2 laterals)	4.41	3.50	−0.91
2005 (2 laterals)	2.85	3.10	0.26
2006 (28 laterals)	5.34	5.86	0.52
Irrigation interval (days)			
2004 (2 laterals)	13.85	16.00	2.15
2005 (2 laterals)	15.13	16.00	0.88
2006 (28 laterals)	15.07	14.96	−0.10
Irrigation flow rate (m^3/s)			
2004 (2 laterals)	0.183	0.254	0.071
2005 (2 laterals)	0.166	0.269	0.103
2006 (28 laterals)	0.320	0.426	0.106

Field Testing

To test the model prediction capability, the model was run in operational mode using 2006 water supply, weather, and crop area data. The RAM at the beginning of the season was set at zero. This was done because in New Mexico soil moisture is minimal at the start of the irrigation season. The irrigation trigger level of RAM at the start of a delivery schedule was also set to zero in order to utilize the entire available soil moisture. The irrigation efficiency and the return flow percentage were both set at 50%, based on the results of previous sensitivity analysis and our literature review (Oad et al. 2007; Lundahl 2006; URS 2005). The return flow percentage is defined as the amount of water that is available in drains from the applied irrigation water that is not used to meet the crop demand. If 100 m^3 are applied at an application efficiency of 50%, and the return flow efficiency is 50%, 25 m^3 will be the water available in drains downstream. The irrigation schedule recommended by the DSS model for 2006 was compared to the actual water delivery practice of ditch riders in 2006. The irrigation duration (time of irrigation), irrigation interval (time between irrigations) and irrigation flow rate during an irrigation season from the model were compared to data collected in the field over a period of 3 years. The field data obtained from ditch riders consists of mean irrigation duration, mean irrigation interval, and mean irrigation flow rate. Figs. 4–6 display the comparison of irrigation duration, irrigation interval, and irrigation flow rate for the 2006 irrigation season, respectively. Table 2 displays the comparison between the DSS and actual practice for mean irrigation duration, mean irrigation interval, and mean irrigation flow rate.

Irrigation duration comparison results are acceptable for most laterals but large discrepancies exist between the model and the actual practice on a significant number of laterals (Fig. 4). The

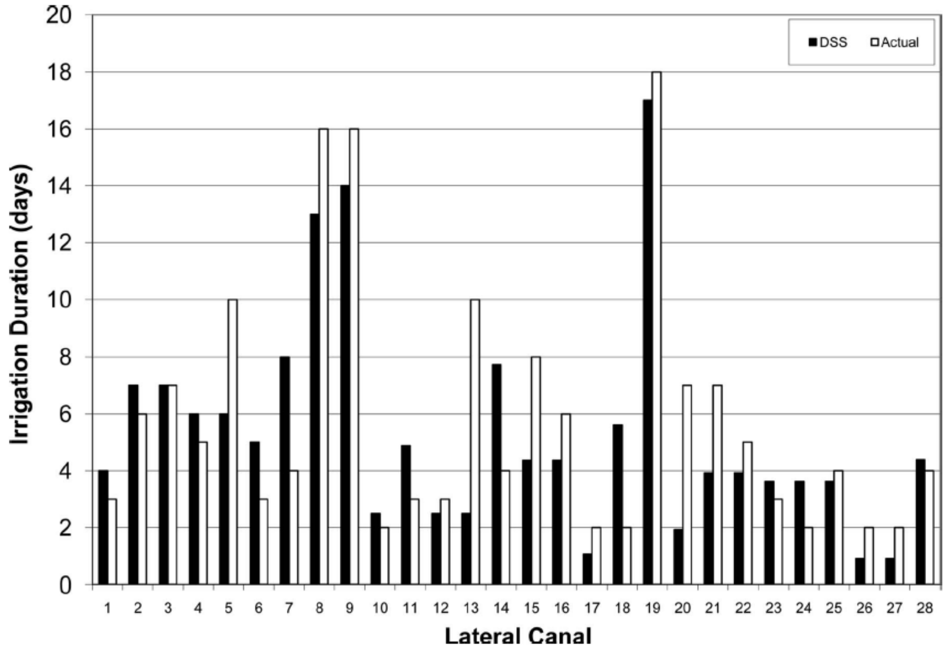

Fig. 4. DSS irrigation duration compared to actual irrigation duration for 28 laterals in 2006

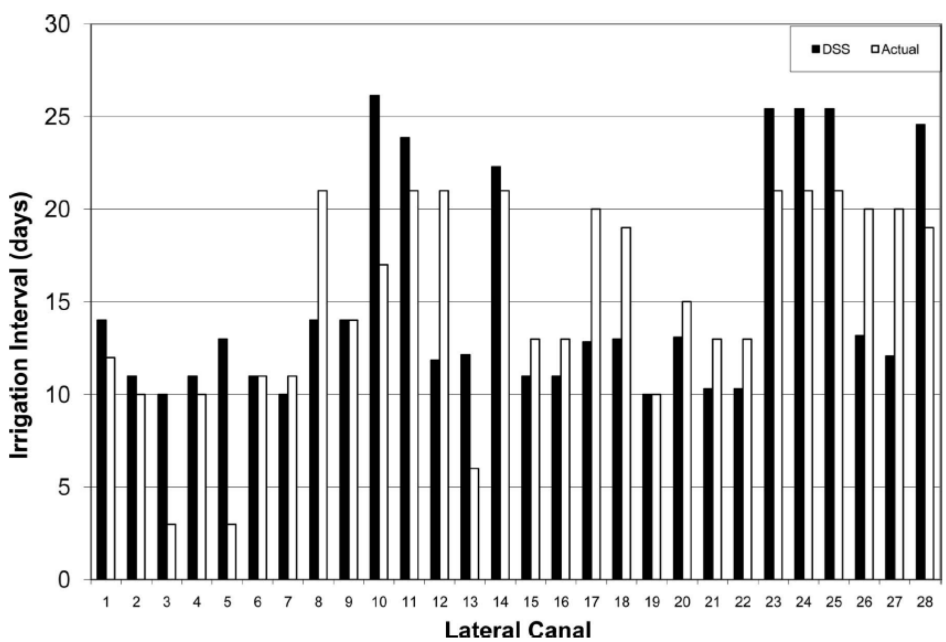

Fig. 5. DSS irrigation interval compared to actual irrigation interval for 28 laterals in 2006

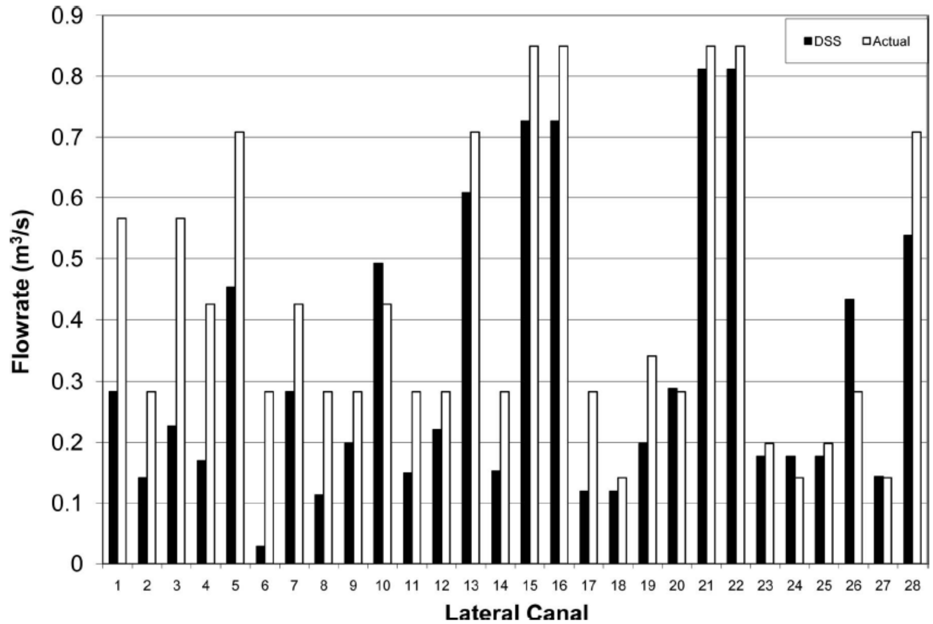

Fig. 6. DSS flow rate compared to actual flow rate for 28 laterals in 2006

difference is largely due to two reasons: the information obtained through the ditch rider interviews is quite subjective and might not reflect the actual irrigation practice, and that the irrigation practice used by ditch riders could be inappropriate. The fact that the 2006 irrigation season was the first time several ditch-riders practiced scheduled water delivery could explain the difference between the optimal duration represented by the DSS and the actual duration used in practice. Ditch riders currently do not have soil moisture probes that can be used to indicate the need for irrigation and their schedules are often arbitrary. Another possible reason for the difference between the DSS recommendations and actual practice is that simplifying assumptions and data inputs for the DSS may not accurately model reality in some cases. The laterals with significant discrepancies warrant further investigation to determine whether the model recommendations are reasonable or if the ditch-riders' practices need change. Future work validating the DSS will involve placing soil moisture probes throughout the MRGCD and examining whether the DSS accurately predicts the depletion of soil moisture.

DSS model values for irrigation interval were slightly longer than the values obtained from the ditch-rider practice, and large discrepancies exist between the model and the actual practice on a significant number of laterals (Fig. 5). The reason for this could be that in actual practice, irrigation events occur before the soil moisture is significantly depleted. Field observations during the 2005 and 2006 irrigation seasons show that oftentimes alfalfa fields were irrigated every 10 days, which is too frequent and would account for the shorter irrigation interval recorded from the field data. Irrigation intervals that are longer than the DSS recommendation indicate that the crops are possibly being stressed.

The actual flow rate proved to be significantly larger than the model recommendations (Fig. 6). This is due to the fact that gauges do not exist on most canals and the flow rate given by the ditch riders is at best an estimate. In the future, staff gauges need to be installed in unchecked canals in order to develop stage–discharge relationships, or automated gates with flow meters need to replace aging lateral turnout structures.

Another aspect of field testing has been to monitor the actual river diversions made by MRGCD at its four main intake points. The results show that using limited scheduled water delivery and infrastructural improvements, the MRGCD has been able to significantly reduce its river diversions. Fig. 7 displays this decreasing trend in annual MRGCD river diversions. Historically, the MRGCD diverted as much as $7.4\times10^8\ \mathrm{m^3/year}$ from the Rio Grande. Over the last 3 years, their diversions have averaged $4\times10^8\ \mathrm{m^3/year}$. Certainly, this is a significant achievement by the MRGCD toward the goal of water conservation and for maintaining stream flows for fish, wildlife, and other ecological needs.

Current schedules in the MRGCD are developed without tools, are based on tradition, and other noncrop-related variables. As schedules are not based on crop demand there is much room for improvement. The current estimated crop requirement is $2.3436\times10^8\ \mathrm{m^3/year}$ and the average diversion is $4\times10^8\ \mathrm{m^3/year}$ indicating that MRGCD can potentially further increase efficiency. This can be done by an effective combination of modernization of control structures, infrastructure improvements, and adoption of management tools such as the DSS.

Implementation

The DSS will be implemented by being incorporated into the MRGCD Supervisory Control and Data Acquisition (SCADA) System. The DSS will give MRGCD operators recommended irrigation delivery on a lateral level based on crop demand, as well

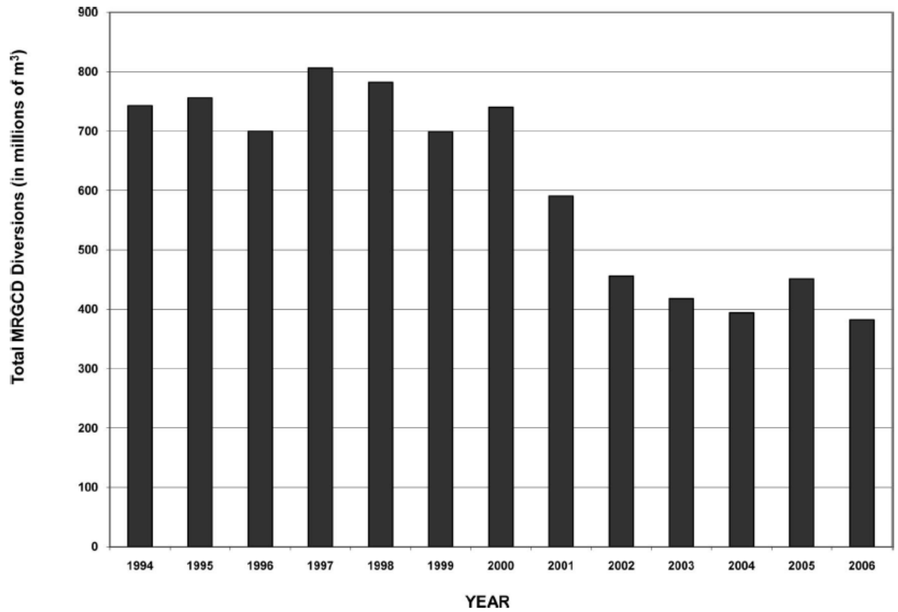

Fig. 7. MRGCD river diversions by year

as the timing of that irrigation. The recommended delivery and timing will be imported into the GUI of the MRGCD SCADA system so that actual deliveries along the canal system can be compared to the required deliveries. The GUI will allow water managers to remotely change automated gate settings so that actual diversions closely represent water requirements. This will provide better water management within the MRGCD and allow for a minimized river diversion as the required and actual diversion values converge.

Conclusions and Further Research

A DSS for the MRGCD has been developed that models the canal network and can compute water delivery options for optimum water use. Using three modules, the model represents water demands, the irrigation network, and water scheduling aspects of irrigation. The model is fully capable of developing schedules for water delivery in the MRGCD, and its evaluation has shown that model recommendations are realistic and have the potential of improving irrigation water delivery efficiency. The MRGCD suggests that efficient irrigation schedules result in a 14–21 day water delivery schedule and the results from the DSS fall within this range.

Future work on the DSS will follow two interrelated paths: a continued emphasis on its field testing and implementation, and its expansion to include the remaining two MRGCD Divisions (Cochiti and Albuquerque). Model accuracy will be tested by monitoring actual soil moisture levels, by utilizing soil moisture sensors, during a period when the model schedule is used exclusively. By determining whether the model effectively manages the moisture in the root zone, revisions and improvements to the model can be made. Once the field investigations are complete, the finalized model can be implemented for scheduling water deliveries throughout the entire MRGCD. Implementation will focus on incorporating the DSS into the already existing MRGCD SCADA system (Gensler et al. 2009). By implementing the DSS for scheduling, the MRCGD will further reduce river diversions and can continue to sustain irrigated agriculture in the Middle Rio Grande Valley.

Acknowledgments

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APPENDIX C: IRRIGATED ACREAGE BY LATERAL SERVICE AREA FOR THE ENTIRE MRGCD

Div	Service Area	2009	2008	2007	2006	2005	2004	2003
Alb	Alameda Lateral	121	127	173	132	117	116	115
Alb	Alameda Wasteway	8	7	8	3	2	2	2
Alb	Albuquerque Main Canal	156	179	68	86	87	87	89
Alb	Allison Lateral	11	11	12	3	3	3	3
Alb	Algodones Acequia	84	82	110	91	91	91	91
Alb	Archibeque Lateral	16	16	14	7	9	9	10
Alb	Aragon Lateral	4	4	2	1	1	1	1
Alb	Arenal Acequia	58	58	43	53	57	58	57
Alb	Arenal Main Canal	807	837	804	784	840	844	839
Alb	Arenal-Atrisco Feeder	3	3	3	4	3	3	4
Alb	Armijo Acequia	58	50	42	47	51	51	53
Alb	Atrisco Acequia	13	13	14	8	7	8	3
Alb	Atrisco Lateral	1	1	1	0	0	0	0
Alb	Barr Main Canal	462	408	419	387	355	362	366
Alb	Bernalillo Acequia	206	228	232	184	182	183	186
Alb	Beckham Lateral	25	25	23	27	22	22	23
Alb	Bennett Lateral	30	30	32	33	27	27	27
Alb	Bosque Lateral #1	10	8	7	7	7	7	7
Alb	Bosque Lateral #2	42	38	37	39	43	43	43
Alb	Breece Lateral	4	4	3	1	1	1	1
Alb	Butte Lateral	0	0	0	0	0	0	0
Alb	Carey Lateral	29	29	28	27	29	29	27
Alb	Chamisal Lateral	142	136	122	146	155	155	173
Alb	Chamisal Wasteway	7	7	7	8	8	8	8
Alb	Cherry Lateral	40	40	41	45	36	36	36
Alb	Corrales Acequia	338	320	325	323	304	295	349
Alb	Corrales Main Canal	347	353	354	343	344	322	326
Alb	Deramedera Acequia	42	40	51	39	41	41	44
Alb	Durand Lateral	109	101	102	80	76	75	83
Alb	Duranes Lateral	290	290	294	200	222	222	225
Alb	Foraker Lateral	9	8	10	5	5	5	5
Alb	Gallegos Lateral	244	233	232	193	166	166	163
Alb	Garcia Lateral	15	15	23	11	10	10	12
Alb	Griegos Acequia	60	60	63	39	26	25	26
Alb	Griegos Lateral	207	218	244	193	172	172	172
Alb	Gun Club Lateral	231	228	232	194	136	217	216
Alb	Hackman Lateral	7	11	10	4	6	6	6
Alb	Hale Lateral	10	11	8	16	18	18	19
Alb	Harwood lateral	14	14	14	6	8	8	9
Alb	Herrera Acequia	3	3	0	2	1	1	2
Alb	Hubbel Lateral	206	206	205	200	197	198	200
Alb	Indian Lateral	147	145	132	135	130	130	129
Alb	Koogler Lateral	10	9	9	4	4	4	3
Alb	Kramer Lateral	35	35	34	27	30	30	30
Alb	Lane Lateral	20	21	21	8	8	8	9
Alb	Los Anayas Wasteway	13	13	9	9	7	7	7
Alb	Los Padillas Acequia	125	118	120	122	102	112	115

Div	Service Area	2009	2008	2007	2006	2005	2004	2003
Alb	Menaul Lateral	20	19	18	9	10	10	10
Alb	Mercantile Lateral	28	29	27	19	16	16	17
Alb	Mirabel Lateral	12	9	12	12	10	10	13
Alb	Newborn Lateral	37	36	40	41	38	38	38
Alb	Nichols Lateral	59	58	64	77	77	77	77
Alb	Old Albuqerque Lateral	25	26	29	16	14	14	14
Alb	Pajarito Acequia	179	162	145	166	151	152	150
Alb	Pajarito Lateral	70	60	90	68	68	58	58
Alb	Phelan Lateral	124	121	131	110	116	116	119
Alb	Pierce Lateral	10	11	12	7	5	5	7
Alb	Placitas Lateral #1	11	10	6	13	12	12	13
Alb	Placitas Lateral #2	34	33	25	22	22	22	22
Alb	Pueblo Acequia	105	108	95	127	115	115	127
Alb	Rice Lateral	26	29	39	39	39	39	38
Alb	Rogers Lateral	8	4	4	3	3	3	3
Alb	Rubi Lateral	28	27	27	20	18	18	21
Alb	San Jose Lateral	16	16	1	4	4	4	4
Alb	Sandia Acequia	49	59	66	39	45	45	46
Alb	Sandia Interior Ditch	24	24	38	40	40	40	40
Alb	Sandoval Lateral	204	204	201	305	292	277	264
Alb	Santa Ana Acequia	0	24	52	52	48	48	48
Alb	Stotts Lateral	11	4	5	3	3	3	4
Alb	Summerford Lateral	81	90	91	71	76	75	69
Alb	Trujillo Lateral	10	15	18	14	12	13	13
Alb	Wenk Lateral	14	13	13	13	13	13	12
Alb	Williams Lateral	826	494	845	897	873	875	886
Alb	Zearing Lateral	2	2	4	0	0	0	0
Belen	Arroyos Lower Acequia	833	775	812	489	466	466	466
Belen	Arroyos Upper Acequia	130	113	108	108	106	130	152
Belen	Belen Grant # 1	264	248	249	228	221	226	226
Belen	Belen Grant # 2	658	556	542	621	772	772	772
Belen	Belen Highline Canal	2095	1522	1756	926	939	952	866
Belen	Belen New Acequia	1850	1876	1807	1766	1763	1875	1803
Belen	Belen New Wasteway	146	129	69	39	39	39	51
Belen	Belen Old Acequia	191	181	156	147	146	151	151
Belen	Belen Riverside Lateral	14	13	13	8	8	8	8
Belen	Bosque - Smith Lateral	53	58	60	55	56	67	67
Belen	Braught Lateral	104	104	129	108	102	106	106
Belen	Caldwell Lateral	39	63	60	69	50	84	84
Belen	Casa Colorada / Sais Lateral	1088	1088	1088	895	879	885	1025
Belen	Chical Lateral	335	276	276	223	221	294	294
Belen	Chical Lateral Extension	247	296	295	271	262	263	289
Belen	El Cerro Acequia	271	174	166	149	174	183	178
Belen	Enrique Lateral	122	128	129	111	111	105	105
Belen	Gabaldon Lateral	327	334	328	285	250	250	241
Belen	Garcia #1 Lateral	416	519	195	195	188	188	188
Belen	Garcia Extension Acequia	2258	2278	1962	1779	1804	1808	1808

Div	Service Area	2009	2008	2007	2006	2005	2004	2003
Belen	Garcia Upper Acequia	195	158	142	55	54	54	54
Belen	Harlan Henderson Lateral	813	841	1270	1225	753	753	599
Belen	Hells Canyon Lateral	583	689	616	554	541	554	567
Belen	Huning Lateral	332	303	290	262	273	320	320
Belen	Jackson Acequia	117	148	157	122	110	112	113
Belen	Jaral #1 Lateral	502	461	468	450	435	432	372
Belen	Jaral #2 Lateral	189	186	181	199	171	171	171
Belen	Jarales New Acequia	84	87	85	36	35	35	35
Belen	Jarales Old Acequia	1409	1343	1339	819	801	799	777
Belen	La Costancia Lateral	1103	1084	1006	862	823	735	773
Belen	La Joya Acequia	800	800	800	800	800	800	800
Belen	Las Cercas Acequia	361	328	431	336	331	325	326
Belen	Las Nutrias Lateral	760	738	708	757	681	708	761
Belen	Los Chavez Acequia	650	628	513	518	516	630	630
Belen	Los Chavez Lateral	81	48	47	37	39	39	39
Belen	Los Lunas Acequia	923	926	1488	1146	529	529	534
Belen	Middle Upper Acequia	451	281	416	248	253	274	271
Belen	Otero Lateral	819	1036	1076	1086	1062	1049	1884
Belen	Peralta Acequia	285	276	301	197	197	203	204
Belen	Peralta Main Canal	932	1147	1090	1080	1104	980	957
Belen	Rincon Acequia	70	68	68	71	66	66	66
Belen	Sabinal #1 Lateral	574	583	595	504	501	501	764
Belen	Sabinal #2 Lateral	238	228	228	203	201	199	182
Belen	Sais Lateral	943	849	849	944	914	920	1057
Belen	San Fernandez # 1 Acequia	67	67	67	66	64	64	64
Belen	San Fernandez # 3 Acequia	311	33	37	37	46	47	47
Belen	San Fernandez # 4 Acequia	69	70	66	60	60	60	60
Belen	San Juan Acequia	297	288	266	265	264	287	287
Belen	San Juan Main Canal	1758	1855	1706	2194	2011	2019	2034
Belen	San Juan Feeder	2	2	2	3	2	2	2
Belen	Sanchez Acequia	53	43	41	21	20	20	20
Belen	Sausal Lateral	628	636	649	661	648	636	636
Belen	Tibo Feeder	55	51	45	18	17	17	18
Belen	Tome Acequia	843	790	834	810	813	729	711
Belen	Valencia Acequia	351	307	309	262	263	277	325
Belen	Vallejos Lateral	175	200	191	184	183	168	168
Cochiti	Cochiti Main Canal	384	406	387	272	278	262	262
Cochiti	Leyba Lateral	37	47	36	3	3	3	3
Cochiti	Majada Lateral	62	0	0	5	6	6	6
Cochiti	Rivera Lateral	262	242	233	288	179	165	172
Cochiti	Yeso Lateral	30	31	34	29	29	29	29
Socorro	Alamillo Acequia	243	240	256	227	221	346	317
Socorro	Apodaca Lateral	187	184	143	208	206	206	206
Socorro	Chambon Lateral	334	315	333	342	345	367	354
Socorro	Florida Lateral	93	105	79	100	98	108	116
Socorro	Isla Lateral	154	153	144	162	161	174	172
Socorro	Jaral Acequia	251	254	247	259	255	317	293

Div	Service Area	2009	2008	2007	2006	2005	2004	2003
Socorro	Lemitar Acequia	176	172	174	189	190	203	205
Socorro	Lemitar Lateral	602	581	573	671	658	716	709
Socorro	Lemitar Wasteway	875	875	875	904	907	921	918
Socorro	Luis Lopez # 1 Acequia	129	114	152	178	179	204	211
Socorro	Luis Lopez # 2 Acequia	324	200	188	164	165	234	236
Socorro	Morton Lateral	151	151	151	154	154	152	152
Socorro	Mosley Lateral	623	472	472	479	474	474	474
Socorro	Polvadera Acequia	440	438	427	439	429	443	442
Socorro	Rinconada Acequia	12	12	12	12	12	87	87
Socorro	Salangre Acequia	63	56	65	65	65	65	65
Socorro	San Acacia Feeder	16	15	17	10	10	14	14
Socorro	San Antonio Old Acequia	960	1003	910	937	914	984	995
Socorro	San Antonio Lateral	200	207	208	219	217	214	214
Socorro	San Antonito Lateral	263	263	257	270	269	269	269
Socorro	Sarracino Lateral	57	57	57	65	65	68	68
Socorro	Socorro Acequia	506	477	482	472	462	508	494
Socorro	Socorro Center Main	1454	1053	1377	1409	1411	1443	1430
Socorro	Socorro North Main	1743	1726	1744	1728	1570	1468	1484
Socorro	Socorro South Main	2106	2083	2103	2094	2073	2097	2097
Socorro	Vasquez Lateral	258	302	296	356	354	387	387

APPENDIX D: STREAM SUMMARY TABLE FOR ENTIRE MRGCD

Division	Canal Connection	Canal length (miles)	Loss per mile (%)	Maximum Capacity (CFS)
Albuquerque	Albuquerque Main at (650 Feeder) -> Alameda Lateral	8.15	2.73	40
Albuquerque	Albuquerque Main at (650 Feeder) -> AM 6	0.7	0.65	220
Albuquerque	Lane Lateral -> Pueblo Acequia	2.1	2.96	30
Albuquerque	Sandia Acequia -> Sandia Acequia Pueblo Demand Node	1	2.73	40
Albuquerque	Sandia Acequia -> AM 6	3.12	2.84	35
Albuquerque	Chamisal Lateral -> Pueblo Acequia	2	2.96	30
Albuquerque	Griegos Lateral -> Gallegos Lateral	3.2	1.98	80
Albuquerque	Gallegos Lateral -> Hackman Lateral	0.9	3.08	25
Albuquerque	Gallegos Lateral -> Duranes Lateral	1.25	2.07	22
Albuquerque	Gallegos Lateral -> Griegos Acequia	1.39	2.96	30
Albuquerque	Duranes Lateral -> Los Anayas Wasteway	0.55	2.07	75
Albuquerque	Los Anayas Wasteway -> Pierce Lateral	0.55	2.07	75
Albuquerque	Pierce Lateral -> Duranes Acequia	1.9	3.08	25
Albuquerque	650 Feeder Inflow -> Garcia	0.6	2.96	30
Albuquerque	650 Feeder Inflow -> Atrisco Siphon	7.62	0.65	220
Albuquerque	Sandoval Lateral -> Corrales Acequia	5.2	2.52	50
Albuquerque	Sandoval Lateral -> Nichols Lateral	0.87	3.34	15
Albuquerque	DI Corrales Main Canal -> Sandoval Lateral	3.8	2.89	33
Albuquerque	DI Corrales Main Canal -> Summerford Lateral	0.6	3.08	25
Albuquerque	Albuquerque Main Canal Inflow -> AM 1	1.87	1.33	130
Albuquerque	Algodones and Santa Ana Acequia Inflow -> Algodones	2	3.34	15
Albuquerque	Garcia -> Albuquerque Main at (650 Feeder)	0.6	2.96	30
Albuquerque	Atrisco Feeder -> Seepage Inflow Connection	7	2.07	75
Albuquerque	Seepage Inflow Connection -> 650 Feeder Inflow	7	1.44	120
Albuquerque	Atrisco Siphon -> Arenal Main Supenode	0.6	1.23	140
Albuquerque	Atrisco Siphon -> Barr Main Canal	3.6	0.65	220
Albuquerque	Barr Main Canal -> Barr Main Canal Supernode	0.1	2.15	70
Albuquerque	AM 4 -> AM 5	0.17	1.13	150
Albuquerque	AM 4 -> Mercantile Lateral	1.2	3.47	10
Albuquerque	AM 6 -> Lane Lateral	0.9	2.73	40
Albuquerque	AM 1 -> AM 2	0.77	1.13	150
Albuquerque	AM 1 -> Mirabel	0.25	3.47	10
Albuquerque	AM 2 -> Bosque Lateral #1	2.5	3.29	17
Albuquerque	AM 2 -> DI AM 3	1.13	1.13	150
Albuquerque	AM 5 -> Bosque Lateral #2	1.9	3.29	17
Albuquerque	AM 5 -> Corrales Siphon	1.04	1.13	150
Albuquerque	Corrales Pueblo Feeder -> Corrales Supernode	0.5	1.44	120
Albuquerque	Algodones Acequia -> AM 1	0.3	2.84	35
Albuquerque	DI AM 3 -> Sandia Acequia	5.78	2.52	50
Albuquerque	DI AM 3 -> AM 4	3.16	1.13	150

Division	Canal Connection	Canal length (miles)	Loss per mile (%)	Maximum Capacity (CFS)
Albuquerque	DI AM 3 -> Bernalillo Acequia	3.9	2.84	35
Albuquerque	Corrales Siphon -> Albuquerque Main at (650 Feeder)	8.2	1.44	120
Albuquerque	Corrales Siphon -> Corrales Pueblo Feeder	0.5	1.44	120
Albuquerque	Barr Main 1 -> San Jose Lateral	1.4	3.31	16
Albuquerque	Barr Main 1 -> Barr Main 2	2.5	2.15	70
Albuquerque	Barr Main 2 -> Phelan Lateral	0.6	3.34	15
Albuquerque	Barr Main 2 -> Barr Main 3	2.5	2.15	70
Albuquerque	Barr Main 3 -> Williams Lateral	2.1	3.08	25
Albuquerque	Barr Main 3 -> DI Barr Main Canal	3	2.15	70
Albuquerque	Barr Main Canal Supernode -> Barr Main 1	0.1	2.15	70
Albuquerque	Arenal Main 1 ND(Atrisco Feeder) -> Armijo Acequia	1.25	2.73	40
Albuquerque	Arenal Main 1 ND(Atrisco Feeder) -> AREM 1	0.1	1.44	120
Albuquerque	Armijo Acequia -> Pajarito Lateral	2.1	3.08	25
Albuquerque	Armijo Acequia -> Los Padillas Acequia	5.91	3.08	25
Albuquerque	AREM 1 -> Aragon Acequia	0.68	3.67	3
Albuquerque	AREM 1 -> Herrera Acequia	0.38	3.62	5
Albuquerque	AREM 1 -> Arenal Atrisco Acequia Feeder	0.7	2.24	65
Albuquerque	AREM 1 -> DI AREM 2	3.9	1.83	90
Albuquerque	Arenal Atrisco Acequia Feeder -> Armijo Acequia	0.7	2.24	65
Albuquerque	DI AREM 2 -> Pajarito Lateral	0.8	1.69	100
Albuquerque	DI AREM 2 -> AREM 3	1.27	1.83	90
Albuquerque	Pajarito Lateral -> Los Padillas Acequia	3.7	2.24	65
Albuquerque	Los Padillas Acequia -> Indian Lateral	1.66	2.52	50
Albuquerque	AREM 5 -> Kramer	0.3	3.47	10
Albuquerque	AREM 5 -> Indian Lateral	3.68	3.21	20
Albuquerque	AREM 5 -> Placitas 2	2.2	3.21	20
Albuquerque	AREM 3 -> Gun Club Lateral	6.8	2.84	35
Albuquerque	AREM 3 -> AREM 4	1.83	1.83	90
Albuquerque	AREM 4 -> Durand Lateral	1.9	2.96	30
Albuquerque	AREM 4 -> AREM 5	1.86	1.83	90
Albuquerque	AREM 4 -> Wenke Lateral	0.5	2.84	35
Albuquerque	Arenal Main Supenode -> Arenal Main 1 ND(Atrisco Feeder)	0.5	1.44	120
Albuquerque	Seepage Inflow from River -> Seepage Inflow Connection	1	2.52	50
Albuquerque	Placitas 2 -> Placitas 1	1	3.34	15
Albuquerque	AM 6 -> Chamisal Lateral	5	2.63	45
Albuquerque	AM 6 -> AM 7	0.2	1.13	150
Albuquerque	AM 7 -> Griegos Lateral	4.2	1.69	100
Albuquerque	Corrales Pueblo Feeder -> Corrales Pueblo Demand	0.2	2.73	40
Albuquerque	Corrales Supernode -> DI Corrales Main Canal	1.92	2.33	60
Albuquerque	Corrales Acequia -> Corrales Minimum Demand	0.1	2.96	30

Division	Canal Connection	Canal length (miles)	Loss per mile (%)	Maximum Capacity (CFS)
Albuquerque	Sandia Acequia Pueblo Demand Node -> Sandia Pueblo	0.1	2.73	40
Albuquerque	Indian Lateral -> Butte Demand	0.1	2.96	30
Belen	New Belen 1 -> New Belen (ND1)	6.84	2.24	65
Belen	New Belen 1 -> Prison Flume (ND)	6.84	2.73	40
Belen	Isleta Return Flow -> 240 wasteway (ND2)	0.1	1.83	90
Belen	240 wasteway (ND2) -> Los Lunas Lateral (ND1)	0.14	2.33	60
Belen	240 Wasteway (ND1) -> New Belen 1	0.03	2.73	40
Belen	Jaral Lateral #1 -> Jaral Lateral #2	1.37	2.96	30
Belen	Sabinal Lateral #1 -> Jaral Lateral #1	0.02	2.96	30
Belen	Belen High Line 1 -> DI Belen High Line 2	7.26	0.45	265
Belen	New Belen Wasteway (ND4) -> Arroyos Lower Acequia	0	2.84	35
Belen	New Belen Wasteway (ND3) -> New Belen Wasteway (ND4)	1.33	2.84	35
Belen	Los Chavez Acequia -> Old Belen	6.23	3.21	20
Belen	New Belen (ND1) -> Gabaldon	1.39	2.24	65
Belen	Prison Flume (ND) -> Harlen Henderson	0.89	2.73	40
Belen	DI Belen High Line 2 -> Tibo Feeder	9.27	3.34	15
Belen	DI Belen High Line 2 -> DI Belen High Line 3	9.27	0.45	265
Belen	New Belen Wasteway -> New Belen Wasteway (ND3)	0.08	2.84	35
Belen	Tibo Ditch -> Garcia Acequia 2	1.15	3.21	20
Belen	Tibo Feeder -> New Belen 2	0.2	2.73	40
Belen	Tibo Feeder -> Tibo Ditch	0.2	3.34	15
Belen	New Jarales -> New Belen Waste Way (ND6)	0.43	2.84	35
Belen	Belen High Line -> Belen High Line (240 WW)	0.1	0.55	240
Belen	DI Belen High Line 3 -> Sanchez Acequia	1.67	3.08	25
Belen	DI Belen High Line 3 -> DI Belen High Line 4	1.67	0.45	265
Belen	Riverside Lateral (ND1) -> Los Chavez Lateral	8.23	2.73	40
Belen	Riverside Lateral (ND1) -> Lower Belen Riverside Drain (ND1)	8.23	2.24	65
Belen	Arroyos Upper Acequia (ND1) -> Caldwell	0.27	3.42	12
Belen	Arroyos Upper Acequia (ND1) -> Arroyos Upper Acequia	0.27	2.84	35
Belen	Los Chavez Lateral -> Arroyos Upper Acequia (ND1)	6.23	2.84	35
Belen	Los Chavez Lateral -> Belen Riverside	6.23	2.24	65
Belen	Belen Riverside -> Old Jarales	0.79	2.96	30
Belen	Arroyos Upper Acequia -> Rincon	0.11	3.34	15
Belen	Garcia Acequia 2 -> Garcia Acequia (ND1)	0.93	3.08	25
Belen	Garcia Acequia (ND1) -> Garcia Acequia 3	0.71	3.08	25
Belen	DI Belen High Line 4 -> Feeder #3 (ND1)	3.48	1.13	150
Belen	Feeder #3 (ND1) -> Garcia Extension Acequia	0.49	1.69	100
Belen	Feeder #3 (ND1) -> Feeder #3 (ND2)	0.49	1.13	150
Belen	Feeder #3 (ND2) -> Feeder #3 (ND3)	0.02	1.13	150
Belen	Huning Lateral -> Los Chavez Acequia	4.32	2.84	35

Division	Canal Connection	Canal length (miles)	Loss per mile (%)	Maximum Capacity (CFS)
Belen	Los Lunas Lateral (ND1) -> Huning Lateral	1.52	2.52	50
Belen	Los Lunas Lateral (ND1) -> Los Lunas Acequia	1.52	2.42	55
Belen	Belen High Line (240 WW) -> 240 Wasteway (ND1)	3.7	1.13	150
Belen	Belen High Line (240 WW) -> Belen High Line 1	3.7	0.45	265
Belen	Garcia Acequia 3 -> Feeder #3 (ND2)	2.72	1.13	150
Belen	Feeder #3 (ND3) -> Sabinal Lateral #1	0.54	2.73	40
Belen	Belen High Line 1 -> Prison Flume (ND)	7.59	2.73	40
Belen	New Belen (ND1) -> New Belen 2	9.08	2.24	65
Belen	240 Wasteway (ND1) -> 240 wasteway (ND2)	0.03	1.13	150
Belen	Sanchez Acequia -> Garcia Acequia (ND1)	0.55	3.08	25
Belen	240 wasteway (ND2) -> Riverside Lateral (ND1)	0.21	1.13	150
Belen	Los Lunas Acequia -> Harlen Henderson	6.24	2.73	40
Belen	Los Lunas Acequia -> Los Chavez Acequia	5.56	2.73	40
Belen	Garcia Acequia 1 -> New Belen Wasteway	1.91	2.84	35
Belen	Old Belen -> Garcia Acequia 1	5.71	3.08	25
Belen	Los Chavez Acequia -> Garcia Acequia 1	8.68	3.08	25
Belen	New Belen 2 -> New Belen Wasteway	0.5	2.84	35
Belen	Garcia Acequia 1 -> Garcia Acequia 2	2.69	3.08	25
Belen	Garcia Acequia 1 -> New Belen Wasteway (ND3)	1.8	3.08	25
Belen	Sanchez Acequia -> Garcia Acequia 3	1.28	3.21	20
Belen	Sabinal Lateral #1 -> Sabinal Lateral #2	0.91	2.73	40
Belen	Gabaldon -> Sausal Acequia	3.35	2.42	55
Belen	Arroyos Upper Acequia -> New Belen Wasteway (ND4)	2.36	2.84	35
Belen	New Belen Wasteway (ND4) -> New Belen Wasteway (ND5)	0.53	2.84	35
Belen	Rincon -> New Belen Wasteway (ND5)	2.55	2.96	30
Belen	Old Jarales -> New Belen Wasteway (ND5)	1.98	2.96	30
Belen	Lower Belen Riverside Drain (ND1) -> Old Jarales	7.07	2.96	30
Belen	New Belen Wasteway (ND5) -> New Belen Waste Way (ND6)	0.25	2.84	35
Belen	New Belen Waste Way (ND6) -> Sabinal Ditch (ND1)	3.85	2.96	30
Belen	New Belen Wasteway (ND5) -> Sabinal Ditch (ND1)	2.25	2.96	30
Belen	Feeder #3 (ND3) -> Feeder #3 (ND4)	0.58	1.13	150
Belen	Sabinal Ditch (ND1) -> Feeder #3 (ND4)	1.36	3.08	25
Belen	Arroyos Lower Acequia -> Feeder #3 (ND3)	4.55	2.84	35
Belen	Sabinal Ditch (ND1) -> Feeder #3 (ND3)	0.82	2.96	30
Belen	Lower Belen Riverside Drain (ND1) -> New Jarales	8.79	2.24	65
Belen	Jackson -> Otero 2	3.1	3.47	10
Belen	Chical Lateral Inflow -> Chical Lateral	0.1	2.15	70
Belen	Otero 1 -> Otero 2	1.71	3.21	20
Belen	Otero 1 -> Braught	1.71	3.34	15
Belen	Hell Canyon (ND1) -> Hell Canyon 2	2.98	2.52	50

Division	Canal Connection	Canal length (miles)	Loss per mile (%)	Maximum Capacity (CFS)
Belen	Hell Canyon (ND2) -> Enrique	2.78	3.47	10
Belen	Chical (ND1) -> Chical (Ext)	1.02	2.84	35
Belen	PM (ND1) -> Otero 1	1.15	3.21	20
Belen	PM (ND1) -> DI PM 1	1.15	0.65	220
Belen	DI PM 1 -> Jackson	1.35	3.47	10
Belen	DI PM 1 -> PM (ND2)	1.35	0.76	200
Belen	PM (ND2) -> DI PM 2	0.49	1.05	160
Belen	PM (ND2) -> Bosque	0.49	3.21	20
Belen	DI PM 2 -> DI PM 3	0.91	1.44	120
Belen	DI PM 2 -> MiddleUpper Acequia	0.91	2.63	45
Belen	DI PM 3 -> PM (ND3)	2.49	1.56	110
Belen	DI PM 3 -> Valencia	2.49	2.73	40
Belen	PM (ND3) -> PM (ND4)	1.05	1.56	110
Belen	PM (ND3) -> Las Cercas	1.05	2.96	30
Belen	DI PM 4 -> PM (ND5)	0.18	0.6	230
Belen	PM (ND5) -> DI PM 5	0.86	1.56	110
Belen	PM (ND5) -> San Fernandez #4	0.86	3.47	10
Belen	DI PM 5 -> PM (ND6)	0.98	1.56	110
Belen	Chical Lateral -> Chical (ND1)	2.2	2.15	70
Belen	Chical Lateral -> Hell Canyon 1	2.2	2.96	30
Belen	Peralta Inflow -> PM (ND1)	0.1	0.65	165
Belen	Bosque -> Hell Canyon (ND1)	1.8	3.21	20
Belen	Tome Drain -> Peralta Riverside Drain	6	1.69	100
Belen	PM (ND6) -> Tome	0.78	2.63	45
Belen	PM (ND4) -> DI PM 4	0.93	1.56	110
Belen	PM (ND4) -> La Constancia	0.93	2.96	30
Belen	Las Cercas -> Chical (Ext)	3.15	3.21	20
Belen	Tome -> Vallejos	3.3	3.47	10
Belen	San Fernandez #4 -> PM (ND6)	1.02	3.47	10
Belen	Hell Canyon 2 -> Hell Canyon 3	0.35	2.52	50
Belen	Hell Canyon 1 -> Hell Canyon (ND1)	3.25	2.52	50
Belen	Valencia -> Hell Canyon (ND2)	3.34	2.52	50
Belen	DI San Juan Main Canal #1 -> Casa Colorada	0.82	2.73	40
Belen	DI San Juan Main Canal #1 -> DI San Juan Main Canal #2	0.82	0.89	180
Belen	DI San Juan Main Canal #2 -> Las Nutrias Lateral (ND1)	4.42	2.84	35
Belen	DI San Juan Main Canal #2 -> San Juan Main Canal (ND1)	4.42	1.13	150
Belen	Las Nutrias Lateral (ND1) -> Las Nutrias	0.66	2.96	30
Belen	San Juan Main Canal (ND1) -> San Juan Main Canal (ND2)	1.99	1.13	150
Belen	San Juan Main Canal (ND2) -> Belen Grant #2	0.99	3.08	25
Belen	San Juan Main Canal (ND2) -> San Juan Main Canal (ND3)	0.99	1.13	150

Division	Canal Connection	Canal length (miles)	Loss per mile (%)	Maximum Capacity (CFS)
Belen	San Juan Main Canal (ND3) -> Belen Grant #1	1.21	3.08	25
Belen	San Juan Main Canal (ND3) -> DI San Juan Main Canal #3	1.21	1.13	150
Belen	San Juan Main Canal -> DI San Juan Main Canal #1	0.1	0.89	180
Belen	Peralta Riverside Drain -> San Juan Main Canal	0.1	0.89	180
Belen	Otero 3 -> PM (ND6)	4.23	2.84	35
Belen	PM (ND6) -> DI PM 6	0.79	1.56	110
Belen	MiddleUpper Acequia -> Hell Canyon 3	7.99	2.96	30
Belen	Otero 3 -> PM (ND5)	1.76	2.96	30
Belen	Hell Canyon 3 -> Hell Canyon (ND2)	2.03	2.52	50
Belen	Hell Canyon (ND2) -> Tome Drain	3.78	2.52	50
Belen	Las Nutrias Lateral (ND1) -> San Juan Acequia	2.24	3.21	20
Belen	Las Nutrias -> DI San Juan Main Canal #3	4.58	2.96	30
Belen	San Juan Main Canal (ND1) -> San Juan Acequia	2.52	2.96	30
Belen	Casa Colorada -> Sais Lateral	1.25	3.21	20
Belen	Otero 2 -> Otero (ND1)	2	2.63	45
Belen	Otero (ND1) -> Otero (ND2)	0.44	2.63	45
Belen	Otero (ND2) -> Otero 3	2	2.84	35
Belen	Otero (ND1) -> San Fernandez 1	0.65	3.21	20
Belen	Otero (ND2) -> San Fernandez 2	0.55	3.21	20
Belen	San Fernandez 2 -> PM (ND4)	0.55	3.21	20
Belen	Hell Canyon 2 -> El Cerro Acequia	2.76	3.08	25
Belen	MiddleUpper Acequia -> Hell Canyon 2	7.06	3.08	25
Belen	DI PM 6 -> PM ND 7	0.05	1.56	100
Belen	PM ND 7 -> Peralta Riverside Drain	0.05	1.56	100
Cochiti	Square Bowl -> San Felipe Siphon (East)	0.51	3.08	25
Cochiti	Square Bowl -> Angostura Lateral (Pueblo)	2.92	2.96	30
Cochiti	SM ND2 -> SM ND 3	4	2.73	40
Cochiti	SM ND2 -> Rivera Lateral (Non Pueblo)	0.72	3.34	15
Cochiti	SM ND1 -> SM ND2	3.85	2.48	52
Cochiti	SM ND1 -> DI Sili Main North (Pueblo)	0.19	3.08	25
Cochiti	SM ND 4 -> Sili Main Ouflow to River 1	1.5	2.84	35
Cochiti	SM ND 4 -> DI Sili Main South (Pueblo)	4	2.73	40
Cochiti	SM ND 3 -> SM ND 4	4	2.73	40
Cochiti	SM ND 3 -> ND Santa Domingo	1.5	2.96	30
Cochiti	Sili Main Canal Inflow -> SM ND1	2.86	2.24	65
Cochiti	Santa Ana Acequia (Pueblo) -> Santa Ana Acequia to Alb	2	3.21	20
Cochiti	San Felipe Siphon (West) -> San Felipe Ditch (Pueblo)	4.76	3.21	20
Cochiti	San Felipe Siphon (East) -> San Felipe Siphon (West)	0.2	3.21	20
Cochiti	San Felipe Siphon (East) -> Algodones Upper Acequia	2.8	3.21	20
Cochiti	DI Sili Main South (Pueblo) -> Sili Main Outflow to River 2	1.5	2.96	30

Division	Canal Connection	Canal length (miles)	Loss per mile (%)	Maximum Capacity (CFS)
Cochiti	DI CM (SD Pueblo) -> CM ND5	1.1	1.5	115
Cochiti	DI CM (Pueblo) -> CM ND 1	1.1	1.69	100
Cochiti	DI CM (Non Pueblo) -> CM ND2	2.54	1.5	115
Cochiti	Cochiti Main Inflow -> DI CM (Pueblo)	0.25	1.56	110
Cochiti	CM ND6 -> San Felipe East Side (Pueblo)	3.74	2.96	30
Cochiti	CM ND6 -> CM Flume	2.7	2.08	74
Cochiti	CM ND5 -> CM ND6	4.31	1.69	100
Cochiti	CM ND5 -> Augustine Lateral (Pueblo)	7.33	2.73	40
Cochiti	CM ND4 -> SD Community Ditch	2.5	3.08	25
Cochiti	CM ND4 -> DI CM (SD Pueblo)	1.1	1.5	115
Cochiti	CM ND3 -> Majada Lateral (Non Pueblo))	1.55	3.47	10
Cochiti	CM ND3 -> CM ND4	1.1	1.5	115
Cochiti	CM ND2 -> Leyba Lateral (Non Pueblo)	0.63	3.34	15
Cochiti	CM ND2 -> CM ND3	0.31	1.5	115
Cochiti	CM ND 1 -> DI CM (Non Pueblo)	1.1	1.5	115
Cochiti	CM ND 1 -> Baca Lateral (Pueblo)	2	2.96	30
Cochiti	CM Flume -> Square Bowl	2.5	2.08	74
Cochiti	Angostura Lateral (Pueblo) -> Yeso Lateral (Non Pueblo)	1.89	3.47	10
Cochiti	Angostura Lateral (Pueblo) -> Algodones Lower Acequia	1	3.21	20
Cochiti	Algodones Upper Acequia (Pueblo) -> Algodones to Alb	2	3.21	20
Cochiti	Algodones Lower Acequia (Pueblo) -> Santa Ana Acequia	1.48	3.21	20
Socorro	SM ND 8 -> DI Socorro Main Center	4.72	0.65	220
Socorro	SM ND 8 -> Chambron Lateral	0.73	3.08	25
Socorro	DI Socorro Main Center -> Socorro Acequia	5.18	2.73	40
Socorro	DI Socorro Main Center -> SM ND 9	2.84	0.57	235
Socorro	Socorro Acequia -> Florida Lateral	1.15	3.21	20
Socorro	SM ND 9 -> Jaral Acequia	2.06	3.08	25
Socorro	SM ND 9 -> SM ND 10	1.89	0.76	200
Socorro	SM ND 10 -> Luis Lopez Acequia #1	1.46	3.08	25
Socorro	SM ND 10 -> DI Socorro Main South	4.78	0.76	200
Socorro	Luis Lopez Acequia #1 -> Luis Lopez Acequia #2	5.15	3.08	25
Socorro	DI Socorro Main South -> SM ND 11	2.69	0.76	200
Socorro	DI Socorro Main South -> San Antonio Acequia	1.26	2.96	30
Socorro	SM ND 11 -> SM ND 12	1.53	0.76	200
Socorro	Apodaca Lateral -> Mosley Lateral	0.1	2.96	30
Socorro	SM ND 12 -> Mosley Lateral	0.35	2.96	30
Socorro	SM ND 12 -> SM ND 13	1	0.76	200
Socorro	SM ND 13 -> San Antonio Lateral	1.76	2.73	40
Socorro	SM ND 13 -> RF to Bosque del Apache Socorro Main	3.89	1.05	160
Socorro	SM ND 7 -> SM ND 8	1.53	0.6	230

Division	Canal Connection	Canal length (miles)	Loss per mile (%)	Maximum Capacity (CFS)
Socorro	SM ND 7 -> Sarracino Lateral	1.92	3.21	20
Socorro	SM ND 2 -> Alamillio Lateral	1.33	3.21	20
Socorro	SM ND 2 -> DI Socorro Main North	0.25	0.57	235
Socorro	Alamillio Lateral -> Salangre Acequia	1.85	3.21	20
Socorro	SM ND 4 -> Vasquez Lateral	1.14	3.08	25
Socorro	SM ND 4 -> SM ND 5	0.98	0.57	235
Socorro	Socorro Main Inflow -> SM ND 1	0.16	0.57	220
Socorro	Sarracino Lateral -> Chambron Lateral	0.31	3.21	20
Socorro	Lemitar Lateral (ND1) -> Lemitar Lateral (ND2)	3.05	2.63	45
Socorro	Lemitar Lateral (ND1) -> Isla Acequia	1.19	3.34	15
Socorro	Lemitar Lateral (ND2) -> Lemitar Acequia	2.15	3.08	25
Socorro	Lemitar Lateral (ND2) -> Socorro Acequia	2.27	2.52	50
Socorro	SM ND 1 -> SM ND 2	0.18	0.57	235
Socorro	SM ND 1 -> Rinconada Lateral	1.6	3.21	20
Socorro	Lemitar Lateral -> Lemitar Lateral (ND1)	1.23	2.63	45
Socorro	DI Socorro Main North -> SM ND 4	1.81	0.57	235
Socorro	DI Socorro Main North -> Polvadera Acequia	3.59	2.96	30
Socorro	SM ND 5 -> Morton Lateral	0.82	3.21	20
Socorro	SM ND 5 -> SM ND 6	0.16	0.65	220
Socorro	SM ND 6 -> SM ND 7	0.34	0.65	220
Socorro	SM ND 6 -> Lemitar Lateral	2.41	2.63	45
Socorro	SM ND 13 -> San Antonito Lateral	1.21	2.96	30
Socorro	Luis Lopez Acequia #2 -> RF to Bosque Del Apache	4.93	2.96	30
Socorro	San Antonio Acequia -> RF to Bosque Del Apache	3.81	2.73	40
Socorro	SM ND 11 -> Apodaca Lateral	2.31	2.96	30
Socorro	SM ND 2 -> San Acacia Feeder	0.59	3.47	10
Socorro	SM ND 7 -> Lemitar Wasteway	3.61	2.15	70

APPENDIX E: SENSITIVY ANALYSIS TO DETERMINE INPUT PARAMETERS

Sensitivity Analysis to Determine Input Parameters

In order develop and run the DSS it was necessary to determine several input parameters utilizing a preliminary sensitivity analysis. This analysis was carried out using data collected during 2004 and 2005. The target variables during the sensitivity analysis were required irrigation flow, irrigation duration and interval of irrigation which were collected from ditch-riders. The input parameters of conveyance loss, application efficiency and readily available moisture (RAM) remaining were determined using a sensitivity analysis and a direct comparison between the DSS output and actual practice was carried out. The documented irrigation practice on the Braught and Jackson Laterals for the time period of April 1st through August 8th, 2005 was used for the sensitivity analysis.

To develop the DSS it was necessary to perform a sensitivity analysis to determine which model input variables. A sensitivity analysis performed on all three main canal areas in the Belen Division examined the key input variables of application efficiency, conveyance loss and RAM percentage remaining to trigger an irrigation event. The three variables were chosen as the most significant input parameters based on research conducted by Gallea, (2005).

Application Efficiency

To examine the effect of application efficiency on the DSS, the application efficiency was changed from 0% to 100% in 0.5% increments. The DSS was run with the different values and a graph was developed. The graph is displayed in Figure 1. The variables of conveyance loss and RAM percentage remaining to trigger irrigation were set at 1.5% and 25% respectively during the analysis of application efficiency.

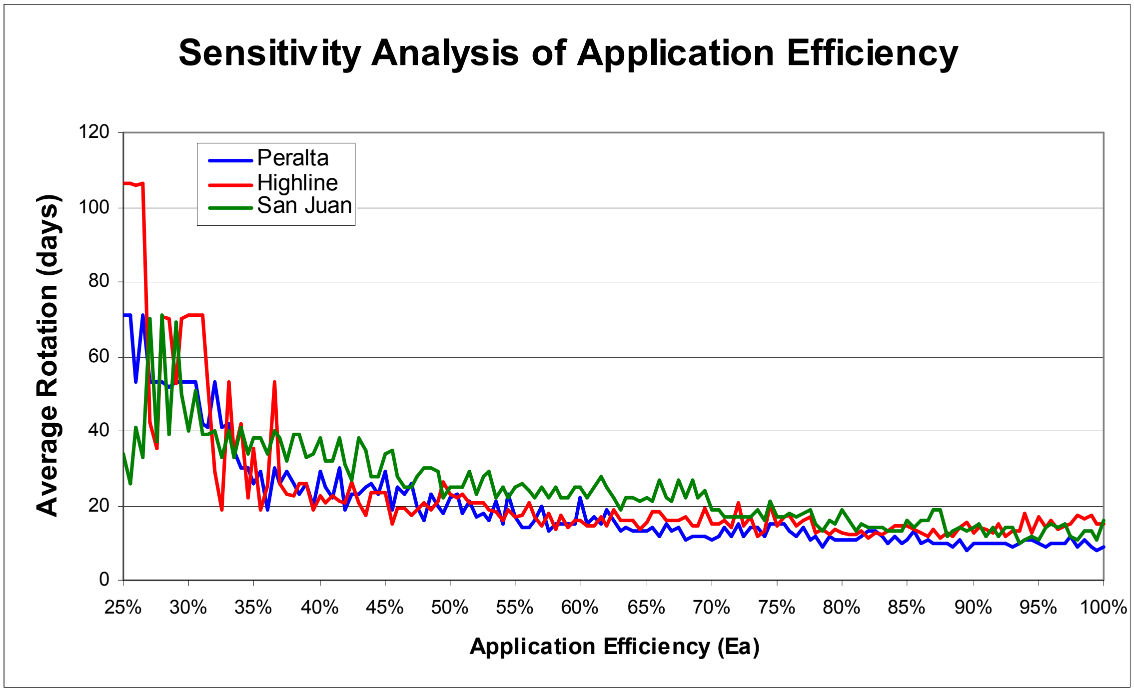


Figure 1. Sensitivity Analysis of Application Efficiency

The graph in Figure 1 showed that as application efficiency decreased the average rotation length increased. As the application efficiency increased the average rotation length decreased, which lead to fewer days of irrigation. Fewer days of irrigation resulting from an increased efficiency would allow for certain ditches to be completely shut down saving large quantities of water.

From the developed graph it became clear that the DSS was not extremely sensitive to changes in application efficiency between the values of 50% and 70%. According to the MRGCD, application efficiencies within the district are between 50 and 65%, which corresponds to the values found during the sensitivity analysis (Gensler, 2005). Using the sensitivity analysis it was possible to select an input value for the application efficiency. The application efficiency for the DSS input was selected to be 50% based on the sensitivity analysis, MRGCD data, and the calibration performed by Gallea (2005).

Conveyance Loss

The next portion of the sensitivity analysis consisted of examining the conveyance loss. To examine the effect of conveyance loss on the DSS, the losses were changed from 0% to 10% in 0.5% increments. The DSS was run with the different values and a graph was developed. The graph is displayed in Figure 2. The variables of application efficiency and RAM remaining were set at 50% and 25%, respectively during the analysis of conveyance loss

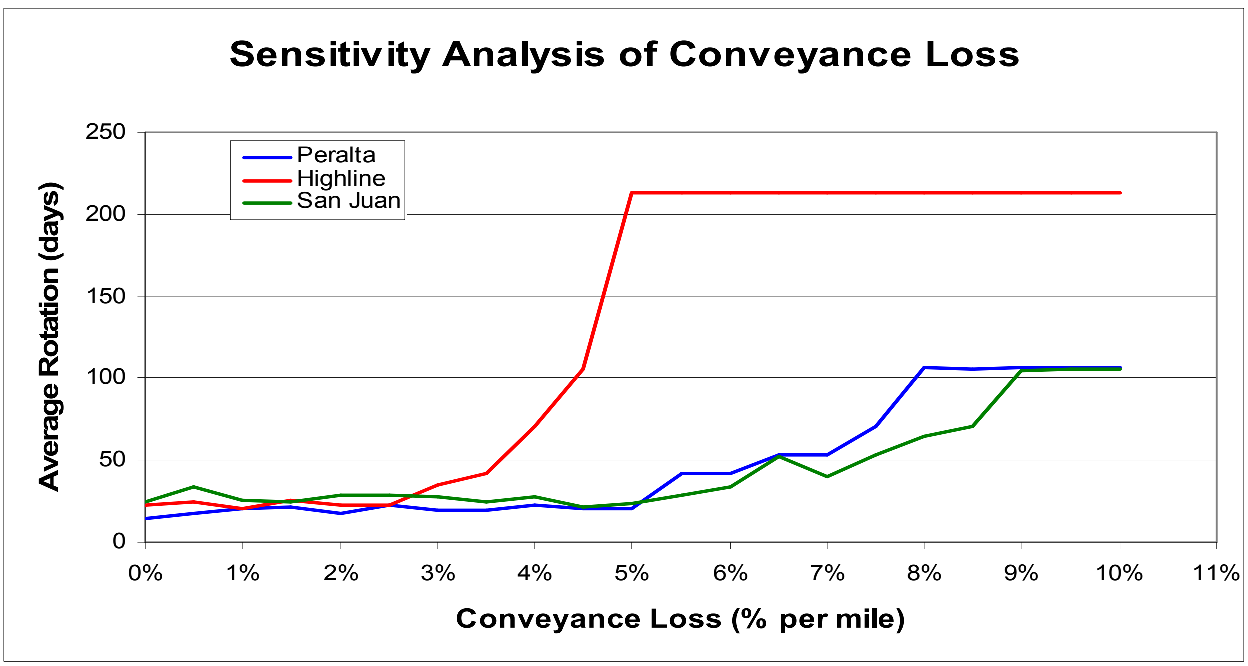


Figure 2. Sensitivity Analysis of Conveyance Loss

Figure 2 showed that as conveyance loss increased, the average rotation length increased as well. Such a result was expected because, as more water is lost, less water is available to meet irrigation requirements. Based on the sensitivity analysis, a conveyance loss of 1.5% per mile represented a reasonable input. This value was chosen due to lack of data and documentation. According to the MRGCD, seepage losses are between 1.5 and 4% per mile throughout the district (Gensler, 2005). Using the results of the sensitivity analysis, the choice of 1.5% per mile is valid because the average rotation length does not change significantly between 1 and 2.5% per mile.

Readily Available Moisture Remaining to Trigger Rotation

The final input variable examined during the sensitivity analysis was the percentage of RAM when irrigation was triggered. To examine the effect of RAM remaining on the model, the RAM at the start of irrigation was changed from 0% to 100% in 0.5% increments. The DSS was run with the different values. The resulting graph is displayed in Figure 3. The variables of application efficiency and conveyance loss were set at 50% and 1.5% respectively, during the analysis of RAM remaining.

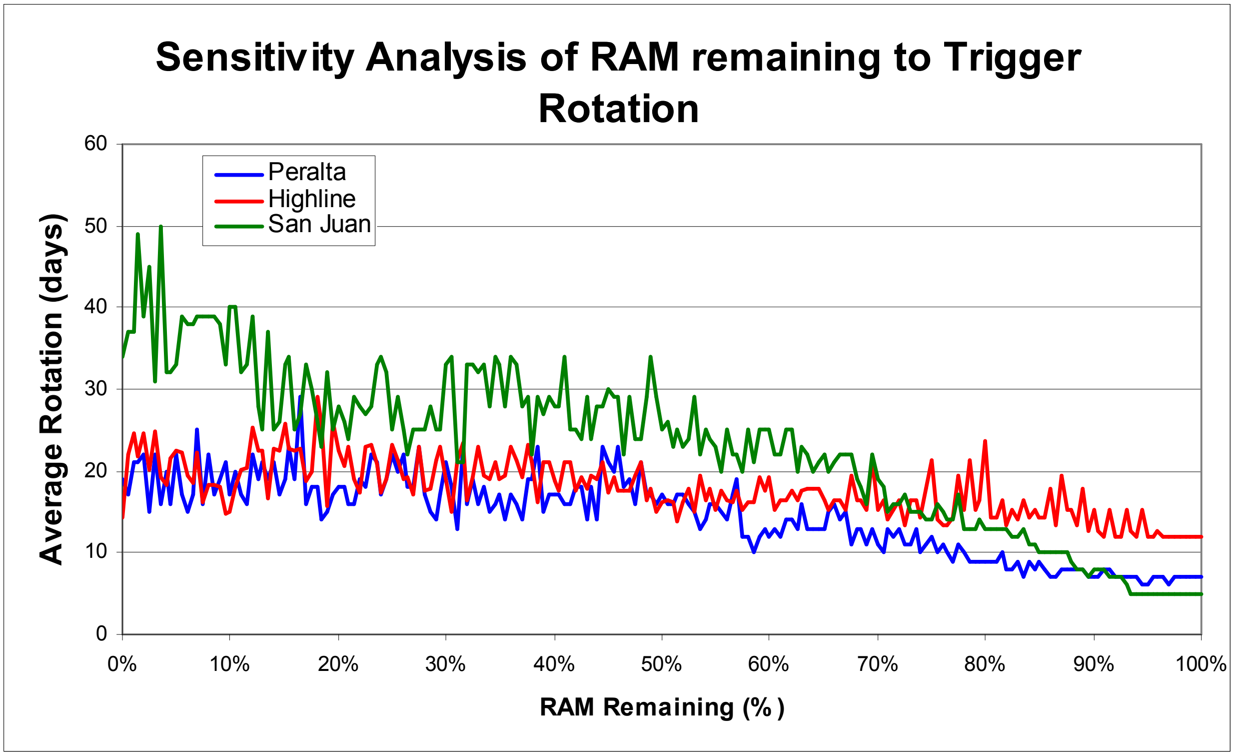


Figure 3. Sensitivity Analysis of RAM Remaining

The developed graph shows that as RAM remaining increases the average rotation length decreases. This makes physical sense because if the RAM remaining at the start of each rotation is high, less water can be stored in the root zone and irrigations have to occur more frequently. Based on the graph in Figure 3, the RAM remaining for irrigation during the development of the DSS was set to 0% to match the MRGCD suggested rotation length of 21 days. This assumption was also based on circumstantial evidence that farmers utilize the entire RAM in the MRGCD.

APPENDIX F: INSTRUMENTATION OF FARM FIELDS

Flow Measurement

The first step in the field instrumentation was to perform a survey to determine the slope of the irrigation head-ditch, which was conducted using a laser level. In addition to the survey, the dimensions of each head ditch were also determined. During the first irrigation event, the flow used for irrigation was measured using a Price Pygmy or Marsh McBirney flow meter. From the collected flow measurement and ditch data, it was possible to design a broad crested weir for flow measurement using the Bureau of Reclamation software Winflume and the Manning's flow equation. The software allows the user to design the appropriate flume and develops a discharge equation based on the head over the crest of the weir. Figure 1 displays the flume designed for Field 3.

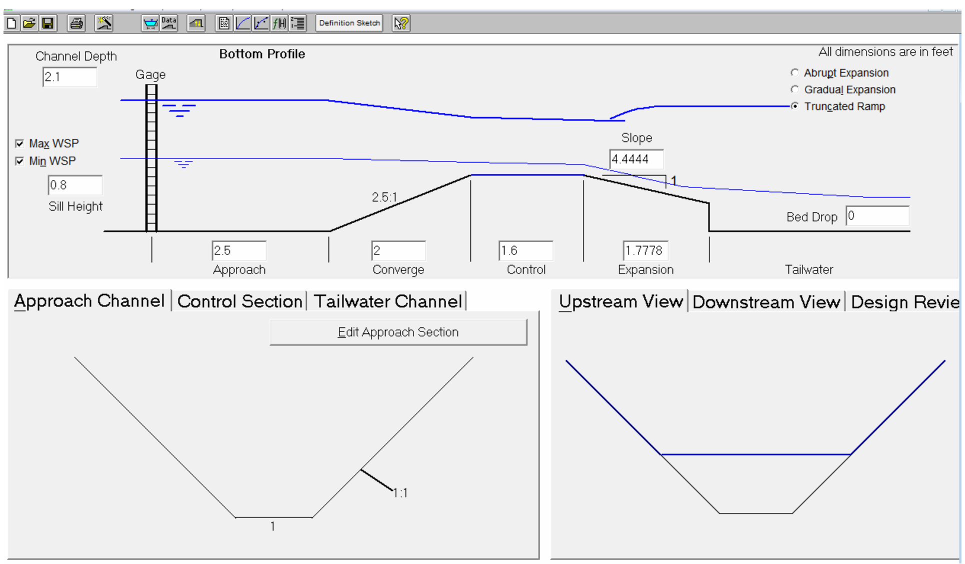


Figure 1: Flume Designed for Measuring Field 3

The broad crested weirs for each field were constructed out of concrete using cutout particle board templates as forms. Broad crested weirs were constructed for each of the eight fields but were utilized on seven fields. One farmer complained that the weir diminished his available flow rate, and therefore a rating curve was developed for his canal section instead of the weir. Figure 2 displays the finished broad crested weir for Field 3.

Figure 2: Completed Broad Crested Weir for Field 3

Hobo pressure transducers and data loggers, manufactured by Onset Incorporated, were installed to measure the depth of water over the crest of the weir. These pressure transducers have an accuracy of 0.01 ft. Figure 3 displays a HOBO pressure transducer.

Figure 3: Hobo Pressure Transducer

The Hobo dataloggers were installed on the side of each irrigation ditch roughly two canal widths upstream of the weir crest (Winflume design standard) using a small length of PVC pipe, clips, and concrete anchors. The section of PVC pipe was perforated with a ¼ inch drill bit to insure that water would seep into the section of PVC and allow for pressure measurement. Once the Hobo data loggers were installed in the PVC pipe a laser level was used to determine the offset between the bottom of the pressure transducer and the top of the weir crest. Figure 4 displays an installed Hobo pressure transducer.

Figure 4: Installed Hobo Pressure Transducer

The Hobo data loggers were set to log the absolute pressure every ten minutes. During an irrigation event, the pressure read by the Hobo included atmospheric pressure, so the atmospheric pressure from a Hobo exposed to only the atmosphere was subtracted from the reading. This resulted in a pressure reading that represented the total depth of water in the irrigation ditch. The pressure reading was converted using the conversion factor that 1 psi is the equivalent of 27.68 inches of water. Once the total depth of water in the irrigation ditch was calculated, the previously mentioned laser leveled offset of the weir crest was subtracted from the total water depth to get the depth of water over the weir crest. This value was plugged into the weir flow rate equation to determine the flow passing the weir every ten minutes. Once the first irrigation event had occurred for each broad crested weir, the flow measurements calculated using the equation were compared to the initial measurement using flow meters in order to insure that the weirs were functioning properly. For each constructed weir the flow rate given by the Winflume equation was reasonable and corresponded to the measurements obtained using flow meters.

The total water volume in cubic feet applied during each irrigation event was obtained incrementally for every ten minute period during the irrigation event. The total volume in cubic feet was calculated by taking the flow rate in cubic feet per second every ten minutes and multiplying this value by 600 seconds. This was done for every ten minute interval during the duration of the irrigation event to obtain the total cubic feet of water applied during the event.

Soil Moisture Measurement

The calculation of the DSS parameters also required the amount of moisture that is stored in the soil for beneficial plant use during the irrigation event and the subsequent depletion of the moisture. To measure the soil moisture, soil moisture probes were installed in each of the eight fields. During early 2008 before the irrigation season, soil moisture probes were installed in the eight representative fields instrumented with broad crested weirs. Electrical conductivity sensors were used instead of time domain reflectrometry (TDR) sensors due to budget constraints. The electrical conductivity sensors used were the EC-20 ECHO probe from Decagon. Figure 5 displays the EC-20 soil moisture probe.

Figure 5: EC-20 ECHO Probe from Decagon Devices

Recent improvements to the ECH20 soil moisture sensor allowed for detailed measurement of soil water content (Sakaki et al. 2008). The ECH2O EC-20, which offers a low cost alternative to other capacitance type meters, (Kizito et al. 2008; Saito et al. 2008; Sakaki et al. 2008; Bandaranayake et al. 2007; Nemali et al. 2007; Plauborg et al. 2005) has been used to improve irrigation management for citrus plantations (Borhan et al. 2004). The precision of the ECH20 EC-20 is such that it can be used for greenhouse operations and to schedule field irrigation (Nemali et al. 2007). The main benefit of the ECH2O sensor is that it is one of the most inexpensive probes available and therefore can be widely used and implemented (Christensen, 2005; Luedeling et al. 2005; Riley et al. 2006). The ECH2O sensor is designed to be buried in the soil for extended periods of time and connected to a data logger such as the Em5b (Decagon Devices, Pullman WA). EC-20 sensors allow for the determination of saturation, field capacity, and wilting point, along with the redistribution pattern of soil water, and possible drainage below the root zone. This information can be used to decide the time and amount of irrigation (Bandaranayake et al. 2007).

The EC-20 probe has a flat design for single insertion and allows for continued monitoring at a user defined interval. The overall length of the sensor is 8 inches with a width of 1.2 inches and blade thickness of 0.04 inches, with a 2.4 inch sensor head length. The total sampling volume of the probe is between 7.8 and 15.6 in^3, depending on soil water content (Bandaranayake et al. 2007). The ECH2O EC-20 soil probe measures the dielectric permittivity or capacitance of the surrounding soil medium, and the final output from the sensor is either in a millivolt or raw count value that can be converted to a volumetric water content using calibration equations (Kelleners et al. 2005). The raw count is an electrical output specific to which datalogger the sensor is used with. Raw counts can easily be converted if an output in millivolts is desired. Details on the EC-20 sensor measurement principle and function are reported by the manufacturer (Decagon Devices, 2006a). Studies have shown that temperature affects on the ECH2O probes are minimal (Kizito et al. 2008; Norikane et al. 2005; Campbell, 2002) with changes of 0.0022 ft^3/ft^3 water content per degree C (Nemali et al. 2007). Problems due to soil variation and air gaps can be avoided by using the factory installation tool and developing calibration equations relevant to each soil type. Drawbacks of this sensor include water leakage into the sensor circuit in isolated cases, and damage from animals such as gophers and squirrels (Bandaranayake et al. 2007). Using the manufacturer provided equation, typical accuracy in medium textured soil is expected to be ±0.04 ft^3/ft^3 (3% average error) with soil specific equations producing results with an accuracy of ±0.02 ft^3/ft^3 (1% average error) (Decagon Devices, 2006b).

Through previous research it has been found that dielectric sensors often require site specific calibration either through field methods or laboratory analyses. Inoue et al (2008) and Topp et al (2000) found that it was necessary to perform site specific calibrations for capacitance sensors to account for salinity concerns, and Nemali et al (2007) found that it was necessary to calibrate the ECH2O sensors because output was significantly affected by the electrical conductivity of the soil. Other studies have found that site specific corrections are required for mineral, organic, and volcanic soils (Paige and Keefer, 2008; Bartoli et al. 2007; Regelado et al. 2007; Malicki et al. 1996).

Kizito et al. (2008) suggested that soil specific calibrations are important when large networks of ECH2O soil moisture sensors are deployed. Several researchers have found that soil specific calibrations are necessary for ECH20 probes across varying soil types (Sakaki et al. 2008; Mitsuishi and Mizoguchi, 2007; Fares and Polyakov, 2006; Bosch, 2004) and Saito et al (2008) found that calibration is a requirement for accurate determination of volumetric water content using the ECH2O. Based on the recommendations of these previous studies, soil specific calibrations were performed for each sensor installation and are presented in a journal article included as Appendix H.

The EC-20 ECHO probes installed in the eight fields were linked to Em5b data recorders. The Em5b is a 5-channel, self-contained data recorder (Decagon, 2008). The Em5b is housed in a white UV-proof enclosure, which makes it suitable for general outdoor measurements. It uses 4 AAA-size alkaline batteries, that last 5-6 months, and has a Flash Data memory that allows for 145 days of data collection at 1 scan/hour (Decagon, 2008). All eight Em5b data loggers were set to record soil moisture every 60 minutes during the study. Figure 6 displays the Em5b data logger.

Figure 6: Em5b-Datalogger from Decagon Devices

The EC-20 ECHO moisture probes were installed in the eight representative fields to obtain a value of soil moisture remaining before an irrigation event and to determine hourly soil moisture depletions. Each field was equipped with one sensor station, due to project budget constraints. This approach resulted in eight point measurements throughout the district. Lundahl (2006) showed that soil moisture measurements at one point in each field were sufficient to obtain soil moisture depletion and application efficiency in the MRGCD. The field layout used for each sensor station is displayed in Figure 7. The layout of the moisture probes was designed to eliminate data points in areas that display variable wetting front values due to distance and the points provided average values for the field in question. Each sensor station consisted of two EC-20 ECHO probes so that a soil profile of up to 4 feet could be measured. Figure 8 displays the layout of a sensor station. The Em5b data loggers were located outside of the field boundary to minimize interference with cultivation and prevent damage of the logger. A 50 ft extension cable was used to place the sensor stations out in the field to eliminate edge effects on crop ET. The 50 ft extension cable was placed in a hand dug trench out into the field at a depth of roughly 8 inches.

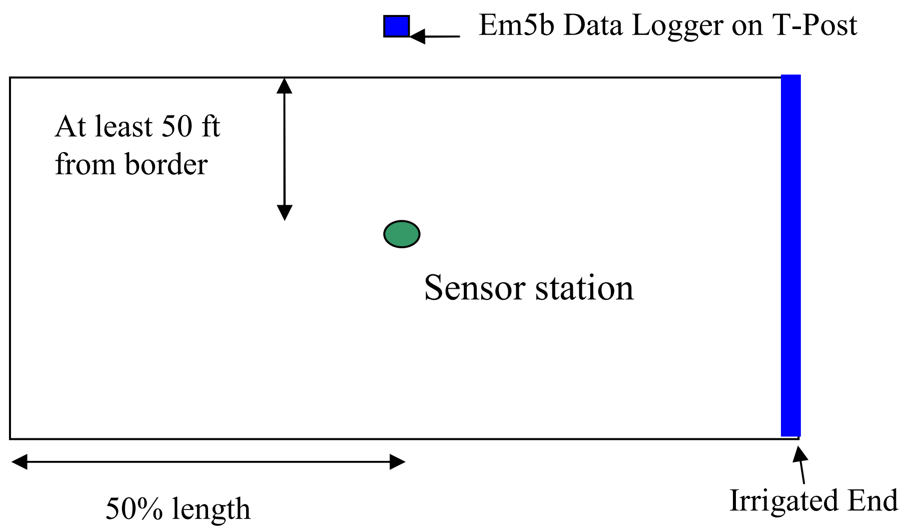


Figure 7: Field Layout of Sensor Stations

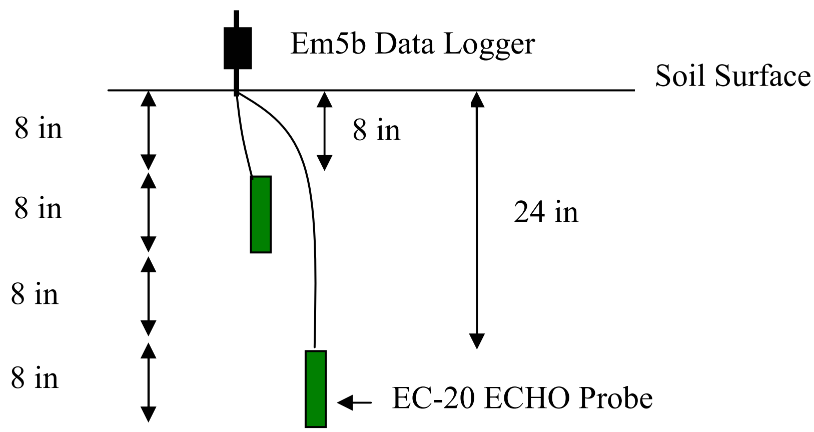


Figure 8: Individual Layout of Sensor Stations

Once the soil moisture probes were installed, GPS points were taken at the location of the sensor station, datalogger, and the corner of the field to determine the exact irrigated acreage. From this collected data and the MRGCD aerial photography coverage, a detailed map of the flume, sensor, and datalogger location was created for each of the eight study fields. Figure 9 displays the map of Field 3. All eight maps are displayed in Appendix G.

Figure 9: Map of Study Field 3

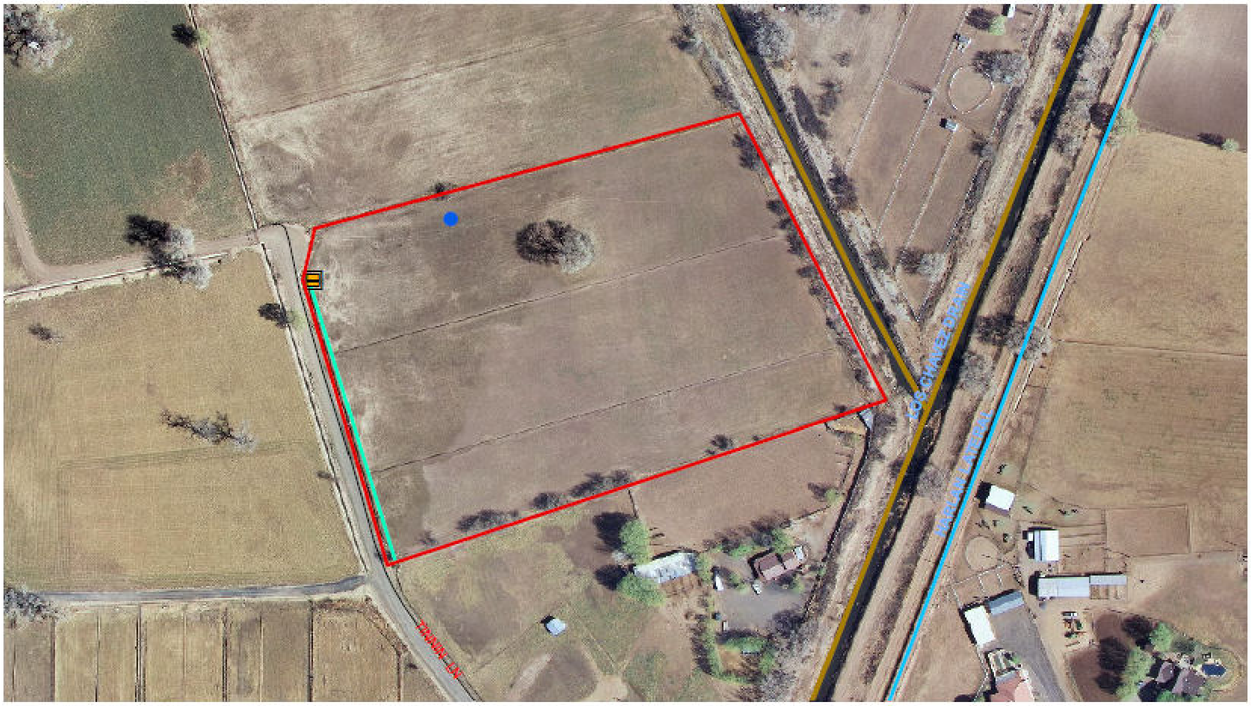
In order to validate that the probes were indeed functioning correctly and to develop calibration equations (presented in Appendix H), soil samples were taken in proximity to the installed sensor stations. A one gallon soil sample was taken for each installed sensor and analyzed at Colorado State University to determine soil type, field bulk density, pH, and electrical conductivity. Soil samples were also taken in order to determine field capacity, wilting point, and RAM for each soil type. These samples were also used to develop soil specific calibration equations for each sensor. The development of soil specific calibration equations is described in the following section. Table 1 displays the results of the soil analysis

Table 1: Soil Characteristics for Monitored Fields in the Middle Rio Grande Valley

Field	Depth (in)	% Sand (> .05mm)	% Silt (.002 to .05mm)	% Clay (< .002mm)	Field Bulk Density (g/cm^3)	Soil Class	pH	EC (ds/m)
3	24	90	5	5	1.594	Sand	7.80	4.29
5	24	96	2	2	1.518	Sand	7.93	3.14
8	24	96	2	2	1.597	Sand	7.58	2.89
3	8	76	14	10	1.54	Sandy Loam	7.79	3.07
4	24	78	16	6	1.68	Sandy Loam	8.07	2.00
7	24	60	29	11	1.511	Sandy Loam	7.75	2.90
8	8	67	19	14	1.478	Sandy Loam	6.95	1.73
1	24	23	52	25	1.617	Silt Loam	7.71	2.71
2	24	44	48.5	7.5	1.555	Loam	7.85	4.39
4	8	43	31	26	1.467	Loam	7.62	3.80
5	8	36	48	16	1.369	Loam	7.41	6.29
7	8	43	35	22	1.544	Loam	7.72	3.20
1	8	40	27.5	32.5	1.420	Clay Loam	8.03	3.51
6	8	23	50	27	1.474	Clay Loam	7.75	4.00
6	24	23	47	30	1.522	Clay Loam	7.87	3.60
2	8	20	27.5	52.5	1.406	Clay	7.85	5.23

APPENDIX G: MAPS OF INSTRUMENTED FARM FIELDS

LOGGER ID - 1



CROP TYPE - Alfalfa Hay

ACREAGE - 9.852

LATERAL - New Belen Acequia

LEGAL DESCRIPTION - Ld of Charles H Rundles

DRLOG ID - 3060352

LEGEND

FLUME

MOISTURE SENSOR

IRRIGATION DITCH

0 100 200 400

Feet

N

MIDDLE RIO GRANDE CONSERVANCY DISTRICT

LOGGER ID - 2

CROP TYPE - Alfalfa Hay

ACREAGE - 12.610

LATERAL - Old Jarales Acequia

LEGAL DESCRIPTION - Plt of Svy of Trs 1 & 6B MRGCD Map 103

DRLOG ID - 3090355

LEGEND

FLUME

MOISTURE SENSOR

IRRIGATION DITCH

0 150 300 600

Feet

N

LOGGER ID - 3

CROP TYPE - Alfalfa Hay

ACREAGE - 10.780

LATERAL - Gabaldon Lateral

LEGAL DESCRIPTION - Ld of Robert Garcia

DRLOG ID - 3060530

LEGEND

FLUME

MOISTURE SENSOR

IRRIGATION DITCH

0 150 300 600

Feet

N

MIDDLE RIO GRANDE CONSERVANCY DISTRICT

LOGGER ID - 4

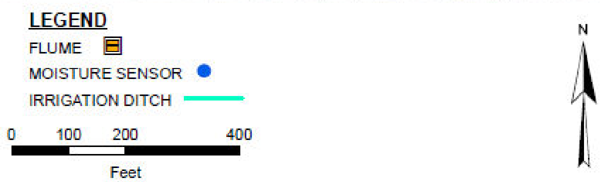
CROP TYPE - Grass Hay

ACREAGE - 4.400

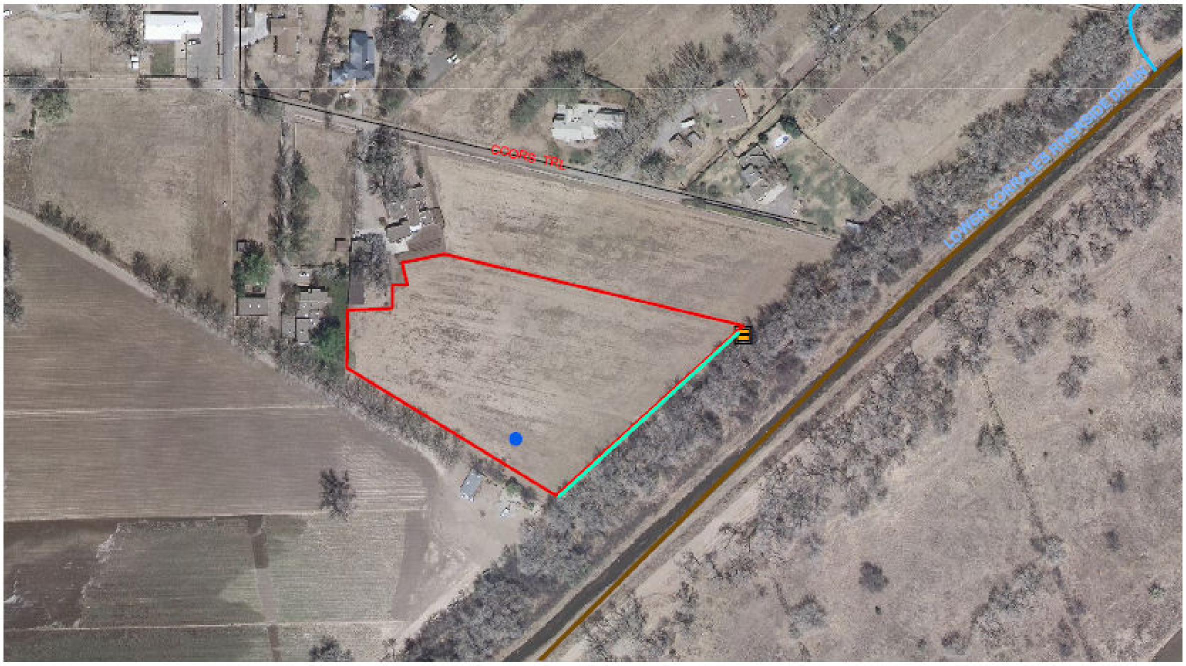
LATERAL - Sabinal #1 Lateral

LEGAL DESCRIPTION - Svy & Plt ld of Jose I Baldonado

DRLOG ID - 3110389



LOGGER ID - 5



CROP TYPE - Grass Hay

ACREAGE - 3.655

LATERAL - Summerford Lateral

LEGAL DESCRIPTION - Plt of Lts 4A 4B & 4C Tr 6 of Lds of Charles A Porter

DRLOG ID - 203844, 203845, 203846, 203847

LEGEND

FLUME

MOISTURE SENSOR

IRRIGATION DITCH

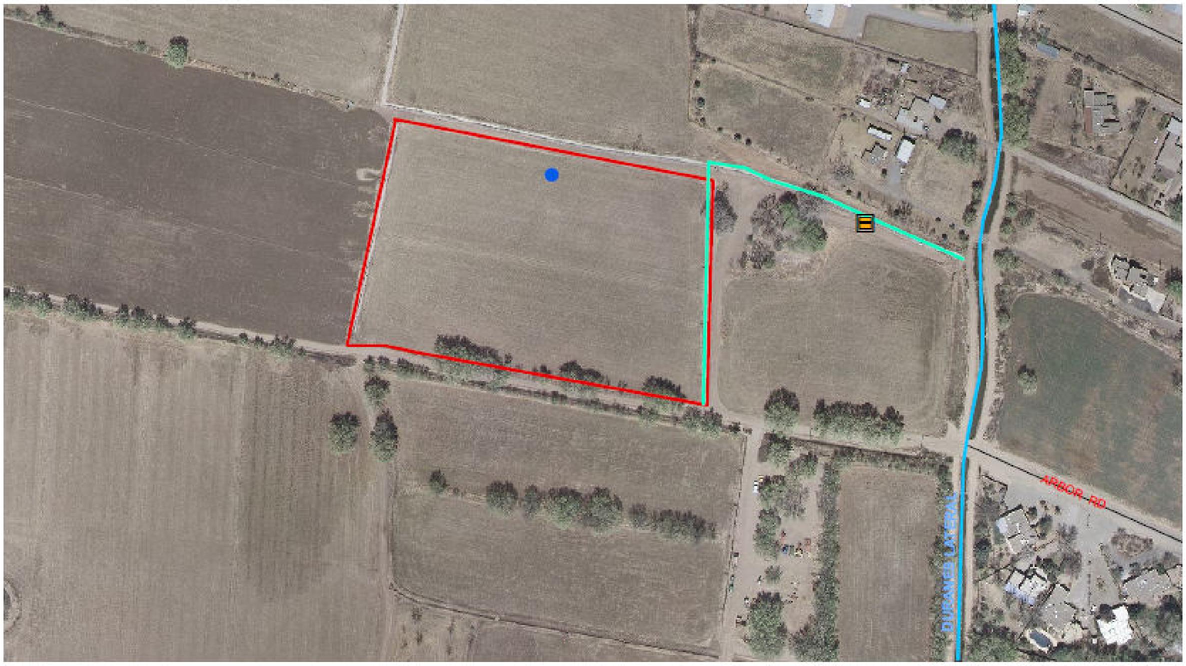
0 100 200 400

Feet

N

MIDDLE RIO GRANDE CONSERVANCY DISTRICT

LOGGER ID - 6



CROP TYPE - Alfalfa Hay

ACREAGE - 5.417

LATERAL - Duranes Lateral

LEGAL DESCRIPTION - Rev Plt of Trs A1 A2 B1 and B2 Candelaria Farms Area

DRLOG ID - 2070064

LEGEND

FLUME

MOISTURE SENSOR

IRRIGATION DITCH

0 100 200 400

Feet

N

MIDDLE RIO GRANDE CONSERVANCY DISTRICT

LOGGER ID - 7

CROP TYPE - Grass Hay

ACREAGE - 4.485

LATERAL - Los Chavez Acequia

LEGAL DESCRIPTION - Lds of Juan Gabaldon

DRLOG ID - 3030631

LEGEND

FLUME

MOISTURE SENSOR

IRRIGATION DITCH

0 100 200 400

Feet

N

MIDDLE RIO GRANDE CONSERVANCY DISTRICT

LOGGER ID - 8

CROP TYPE - Grass Hay

ACREAGE - 2.714

LATERAL - Williams Lateral

LEGAL DESCRIPTION - Map 55 Tr. 1A

DRLOG ID - 2100093

LEGEND

FLUME

MOISTURE SENSOR

IRRIGATION DITCH

0 100 200 400

Feet

N

MIDDLE RIO GRANDE CONSERVANCY DISTRICT

APPENDIX H: KINZLI, MANANA, AND OAD (IN PRESS)

A COMPARISON OF LABORATORY AND FIELD CALIBRATION OF THE ECH2O EC-20 SOIL MOISTURE PROBE FOR SOILS IN THE MIDDLE RIO GRANDE VALLEY

A Comparison of Laboratory and Field Calibration of the ECH20 EC-20 Soil Moisture Probe for Soils in the Middle Rio Grande Valley

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Abstract

Throughout the American West irrigated agriculture has been targeted to increase water use efficiency. Soil moisture sensors offer a method to achieve efficiency improvements but have found limited use due primarily to high cost and lack of soil specific calibration equations. In this paper we examined the ECH2O EC-20 soil moisture sensor, a low cost capacitance sensor and developed a unique laboratory calibration method. Field and laboratory calibration equations were developed for 6 soil types in the Middle Rio Grande Valley. The average absolute error in volumetric water content for field calibration was 43.3%, and 1.22% for the laboratory calibration. The factory calibration equation for the EC-20 was also evaluated and found to yield an average absolute error of 3.98%.We found that the EC-20 is a reliable, cost effective, and accurate sensor, and recommend that the laboratory calibration method presented here be used to obtain maximum accuracy.

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Introduction

Agricultural water use regulations have become increasingly stringent over the last several decades due to increased urbanization, population growth, and ecological concerns (Gensler et al. 2009; Nemali et al. 2007; Grigg 1996). Irrigated agriculture uses roughly 80–90% of surface water in the American west, and is often targeted to increase water use efficiency (Oad et al. 2009) and soil moisture measurement offers a method for achieving this improvement. Monitoring of soil moisture is beneficial for precision agriculture (Saito et al. 2008) and soil moisture sensors can be used to schedule irrigation and minimize overall water use (Hansen et al. 2000). Accurate measurement of soil moisture is crucial for determining crop response to water stress, and for practical applications such as irrigation scheduling (Mwale et al. 2005). Through the use of soil moisture sensors optimal irrigation quantity and timing can be determined (Paige and Keefer, 2008). In order to realize precision irrigation scheduling it is crucial to monitor crop depletions and soil moisture sensors provide the capability to measure these depletions. In addition to scheduling precision irrigation it is important to continuously measure water content for better agricultural management (Inoue et al. 2008). Such management could reduce production costs, wasting of water, leaching of applied fertilizer and pollution of groundwater.

Monitoring soil moisture through the use of soil moisture probes can also be beneficial to natural resource management by determining hydrologic variables such as surface runoff, infiltration, evaporation, and transpiration (Saito et al. 2008). Soil moisture sensors can also be used to determine the affect that changes in soil moisture have on hydrology, meterology, microclimate, and overall watershed conditions (Paige and Keefer, 2008; Kaleita et al. 2005). Additionally, soil moisture sensors can be used for a variety of applications such as water balance, hydrologic flux, rainfall input, and water supply calculations. (Paige and Keefer, 2008). Soil moisture is an important component of the overall water balance and can be especially crucial for agricultural and rangeland management (Paige and Keefer, 2008).

The Middle Rio Grande Valley in central New Mexico is a prime example of a region where agricultural water users have been targeted to increase water use efficiencies due to increasing demands, interstate compacts, and instream flow requirements linked to federally listed endangered species. To improve water delivery efficiencies the New Mexico Interstate Stream Commission and the Middle Rio Grande Conservancy District have developed a Decision Support System over the last several years. The Decision Support System monitors soil moisture levels and crop depletion, and schedules irrigation water deliveries according to crop demand which increases water delivery efficiencies (Oad et al. 2009; Gensler et al. 2009). In order to validate the moisture depletion calculated using the Decision Support System it was necessary to deploy soil moisture sensors in several fields and determine actual depletions. To ensure that the data collected was as accurate as possible both laboratory and field calibration equations for moisture sensors were developed throughout the Middle Rio Grande Valley.

Many techniques exist to measure field soil water content. The standard method is gravimetric sampling which requires knowledge of the sample volume or a separate bulk density sample (Kaleita et al. 2005). In past studies tensiometers have been used but do not offer data logging and must be continuously filled with water throughout the irrigation season. Additionally, tensiometers can be destroyed by equipment during normal field operations. In recent years multiple sensor types have become available to continuously measure soil moisture content. Despite the availability of tensiometers (Krüger, 1999; Smajstrla and Locascio, 1996) neutron probes (McFall, 1978; Gear et al. 1977) and time domain reflectometry (TDR) sensors, moisture sensors are rarely used to schedule irrigation (Nemali et al. 2007). The main reason for limited use of the above sensors is that high costs, unsuitable size, required effort, and reliability of sensors prevent widespread use for irrigation scheduling (Nemali et al. 2007).

Many different manufacturers offer a dielectric probe for measuring soil water content. These type of sensors measure the dielectric constant of the soil, the value of which is determined predominantly by its moisture content. This value can then be converted into a volumetric water content using either factory or site specific calibration equations. Moisture sensors based on dielectric properties provide scientists with a powerful tool for real time soil moisture measurement as well as continued data logging (Inoue et al. 2008) at a fraction of the price of other methods. Additionally capacitance probes can be used at multiple depths (Evett and Steiner, 1995; Paltineau and Starr, 1997) to develop a profile across a crop root zone. One drawback of capacitance type sensors is that they can be affected by extreme temperatures and salinity (Baumhardt et al. 2000; Wraith et al. 1999; Topp et al. 1980)

A probe that has recently become available (Nemali et al. 2007) and has found implementation is the ECH20 EC-20 (Decagon Devices, Pullman, WA, 2006b) dielectric probe from Decagon Devices. Recent improvements to the ECH20 soil moisture sensor allow for detailed measurement of soil water content (Sakaki et al. 2008). The ECH2O EC-20, which offers a low cost alternative to other capacitance type meters, (Kizito et al.

2008; Saito et al. 2008; Sakaki et al. 2008; Bandaranayake et al. 2007; Nemali et al. 2007; Plauborg et al. 2005) has been used to improve irrigation management for citrus plantations (Borhan et al. 2004) and the precision of the ECH20 EC-20 is such that it can be used for greenhouse operations and to schedule field irrigation (Nemali et al. 2007). The main benefit of the ECH2O sensor is that it is one of the most inexpensive probes available and therefore can be widely used and implemented (Christensen, 2005; Luedeling et al. 2005; Riley et al. 2006). The ECH2O sensor is designed to be buried in the soil for extended periods of time and connected to a data logger such as the EM5B (Decagon Devices, Pullman WA). EC-20 sensors allow for the determination of saturation, field capacity, and wilting point, along with the redistribution pattern of soil water, and possible drainage below the root zone. This information can be used to decide the time and amount of irrigation (Bandaranayake et al. 2007).

The EC-20 probe has a flat design for single insertion and allows for continued monitoring at a user defined interval. The overall length of the sensor is 20.5cm with a width of 3.1cm and blade thickness of 0.1cm, with a 6 cm sensor head length (Figure 1). The total sampling volume of the probe is between 128 and 256 cm^3 depending on soil water content (Bandaranayake et al. 2007). The ECH2O EC-20 soil probe measures the dielectric permittivity or capacitance of the surrounding soil medium and the final output from the sensor is either in a millivolt or raw count value that can be converted to a volumetric water content using calibration equations (Kelleners et al. 2005). The raw count is an electrical output specific to which datalogger the sensor is used with. Raw counts can easily be converted if an output in millivolts is desired. Details on the EC-20 sensor measurement principle and function are reported by the manufacturer (Decagon

Devices, 2006a). Studies have shown that temperature affects on the ECH2O probes are minimal (Kizito et al. 2008; Norikane et al. 2005; Campbell, 2002) with changes of 0.0022 m^3/m^3 water content per degree C (Nemali et al. 2007). Problems due to soil variation and air gaps can be avoided by using the factory installation tool and developing calibration equations relevant to each soil type. Drawbacks of this sensor include water leakage into the sensor circuit in isolated cases, and damage from animals such as gophers and squirrels (Bandaranayake et al. 2007). Using the manufacturer provided equation typical accuracy in medium textured soil is expected to be ± 0.04 m^3/m^3 (3% average error) with soil specific equations producing results with an accuracy of ± 0.02 m^3/m^3 (1% average error) (Decagon Devices, 2006b)

Through previous research it has been found that dielectric sensors often require site specific calibration either through field methods or laboratory analyses. Inoue et al (2004) and Topp et al (2000) found that it was necessary to perform site specific calibrations for capacitance sensors to account for salinity concerns and Nemali et al (2007) found that it was necessary to calibrate the ECH2O sensors because output was significantly affected by the electrical conductivity of the soil. Other studies have found that site specific corrections are required for mineral, organic, and volcanic soils (Paige and Keefer, 2008; Bartoli et al. 2007; Regelado et al. 2007; Malicki et al. 1996). Kizito et al (2008) suggested that soil specific calibrations are important when large networks of ECH2O soil moisture sensors are deployed. Several researchers have found that soil specific calibrations are necessary for ECH20 probes across varying soil types (Sakaki et al. 2008; Mitsuishi and Mizoguchi, 2007: Fares and Polyakov, 2006; Bosch, 2004) and Saito et al (2008) found that calibration is a requirement for accurate determination of volumetric water content using the ECH2O. Despite the need for site specific calibration limited published data for ECH20 sensors are available and further studies on the EC-20 are needed (Saito et al. 2008; Sakaki et al. 2008; Bandaranayake et al. 2007; Norikane et al. 2005; Bosch, 2004).

The standard Decagon calibration equation using millivolts for the EC-20 is given as:

$\Theta = -0.29 + 0.000695(mV)$. **EQ 1**

For the Em5B Decagon logger output of rawcounts the equation is:

$.000424(rawcount) - .29$. **EQ 2**

In some instances, such as the use of a datalogger other than the Decagon loggers it may be necessary to convert between millivolts and raw counts. If millivolt output is desired the rawcounts can be converted for the Em5b datalogger using the following equation:

mV= [rawcounts (3000 (logger excitation voltage))]/4096 **EQ 3**

Laboratory calibration of the EC-20 can be completed by performing a series of measurements on multiple soil samples with varying moisture content and regression. This method has proven successful for the calibration of several diaelectric instruments (Seyfried and Murdock, 2004; Veldkamp and O'Brien, 2000). Field calibration can be accomplished through regression with numerous gravimetric samples and is an approach that has been used in the calibration of capacitance probes and TDR sensors (Geesing et al. 2004; Walker et al., 2004; Kelleners et al., 2004; Morgan et al., 1999).

The objectives of this study were to;

1) Perform a field calibration of the ECH20 EC-20 soil moisture sensor for various soil types in the Middle Rio Grande Valley
2) Perform laboratory calibrations using a modified method for the ECH20 EC-20 soil moisture sensor for various soil types in the Middle Rio Grande Valley
3) Compare the laboratory and field calibrations and evaluate the laboratory method and;
4) To determine the difference both methods display in regards to the manufacturers generic calibration equation

The goal of this research was to provide irrigators and researchers with a precise laboratory calibration method, specific lab and field calibration equations, and an understanding of what accuracy can be expected using various calibration methods for the ECH2O EC-20 soil moisture sensor. Although the focus of this research is related to irrigated agriculture other users of soil moisture sensors in various applications could benefit from this research.

Material and Methods

Eight fields, irrigated using border and flood irrigation, within the Middle Rio Grande Valley were chosen for soil moisture monitoring. Two ECH20 EC-20 soil moisture probes were installed in each field at a depth of 8 inches and 24 inches. The NRCS recommends installing soil moisture sensors at 6-8 inches and 18-20 inches to obtain profiles in the Middle Rio Grande Valley. The sensors were installed 50ft into the field away from the border to minimize edge effects by digging a shallow trench into the field at a distance of one half the field length from the irrigated end. This ensured that the sensors would be obtaining a representative measurement while not impeding field trafficability.

This resulted in a total deployment of 16 ECH20 EC-20 sensors. During installation a one gallon soil sample was obtained from each depth in order to determine soil type, electrical conductivity, and perform laboratory sensor calibrations. All probes were installed using the factory recommended tools consisting of an auger, blade for making a pilot hole, and the ECH2O insertion tool. The insertion tool is critical for the installation of the EC-20 sensors as it prevents the sensor from being snapped while it is being inserted. The installed sensors were connected to an EM5b datalogger, mounted on a T-post at the edge of the field, which reads electrical rawcounts of the EC-20 sensor. The Em5B was set to record soil moisture every 60 minutes. Figure 2 displays the location of the fields instrumented with EC-20 sensors.

In order to determine soil type for all 16 installation locations both sieve and hydrometer analyses were completed. In addition to this analysis electrical conductivity was determined for each soil using the 1:1(V:V) soil: water extract method and a HATCH HQ 40d electrical conductivity sensor.

Field Calibration

Throughout the irrigation season gravimetric samples were taken for each of the 16 deployed sensors in close proximity of the sensor. The collection of the samples was timed to account for pre and post irrigation soil moisture levels. Overall, five measurements with two replicates per measurement were collected for each sensor installation. The samples were collected using an Oakfield Soil Sampling Auger and airtight soil moisture tins. These samples were weighed and oven dried at 105^0C for 24h and reweighed to determine volumetric water content. This volumetric water content was correlated to a rawcount reading from the Em5b datalogger for the hour during which the sample was taken. Since an Oakfield probe was used to obtain the samples it was also possible to determine the field bulk density for each measurement occasion.

<u>Laboratory Calibration</u>

Laboratory calibrations were performed using a modified approach to the manufactures suggested calibration method (Decagon, 2006b). For the laboratory calibration of ECH2O EC-20 sensors a 6 inch diameter piece of PVC was used as a calibration cylinder. Before calibration began the soil samples were oven dried for a period of 24h at 105° C. This made it possible to pack the calibration cylinder to the exact bulk density measured in the field and since the calibration cylinder volume was known, it was possible to calculate the weight of dry soil necessary to exactly replicate the field bulk density. Once the oven dry soil was packed into the cylinder at field bulk density the EC-20 sensor was inserted using the manufacturer recommended insertion tool. The probe was allowed to equilibrate, a reading of the raw counts was recorded using an Em5b datalogger, and the probe was removed from the calibration cylinder

Once the probe was removed from the cylinder it was necessary to obtain a volumetric sample to determine soil moisture content for a given sensor output. This was accomplished by using two small cylinders constructed out of copper water pipe with volumes of 23.40 and 23.73 cm^3 respectively. To decrease the affect of compacting the soil in the measurement cylinder the edges of the copper cylinders were beveled to a thin, sharp edge using a metal file. The cylinder and the volume of soil contained in it were then extracted from the test cylinder. The samples were trimmed from the top and bottom edges of the cylinder to ensure accuracy in the volume measurements and emptied into soil moisture sampling tins and weighted. The samples were then placed in an oven at 105^0 C for 24 hours and re-weighted thereafter. Volumetric water content was then calculated for each of the soil samples. Bulk density was also determined and used to verify that the field bulk density was indeed replicated in the calibration cylinder.

This procedure was completed for each of the 16 soil types by subsequently adding 100 ml of water to the soil in the calibration cylinder to increase the moisture content and develop calibration curves. Once readings were obtained from the oven dry sample, the soil inside the calibration cylinder was placed in a pan where 100 ml of water were added. The sample was then mixed for a period of 10 minutes to ensure uniform distribution of the water throughout the soil. Once mixing was complete the soil was packed back into the calibration cylinder at the field bulk density. The EC-20 probe was inserted again, the raw count recorded, and two volumetric samples were removed to determine the water content. This process was repeated until the water content of the soil reached saturation and in most case resulted in at least 7 measurements consisting of a raw count and a soil moisture content. A more detailed explanation of calibrating capacitance probes can be found in Starr and Palineanu (2002) and Polyakov et al. (2005).

From the collected field and laboratory data it was possible to develop predictive regression equations relating raw count to volumetric water content. Both linear and polynomial equations were used to achieve the best fit for each soil type.

In order to determine the accuracy of the factory, and developed field, and laboratory calibration equations, the absolute error between the predicted volumetric water content and the actual measured water content was calculated. The absolute error was selected as being appropriate based on the preliminary findings that several of the field calibration equations exhibited both over and under prediction for the same soil type.

Results

From the soil analysis it was determined that the 16 installation sites were characterized by six soil textures consisting of sand, sandy loam, silt loam, loam, clay loam, and clay. The field bulk densities varied from 1.4 to 1.6 g/cm^3. The EC analysis revealed variations from 2.0 ds/m to 6.29 ds/m. No sample exceeded 8 ds/m where capacitance sensors experience distortion. Table 1 displays the results of the soil analysis.

<u>Field Calibration</u>

The data from the field calibration showed that a significant amount of scatter existed in regards to the factory calibration equation. The data from the field calibration also exhibited that the collected points were clustered together and covered a minimal range of volumetric water contents. The curvature of the collected points was explained using linear, and polynomial, equations (Figure 3). The slope of the curvature for data points collected from the fields was in most cases significantly different from the factory equation slope.

The field calibrations were most successful for sand soils where a larger range of moisture contents was obtained from the field measurements. In the other five soil textures the data collected from the field sampling was bunched together in tight clusters at higher volumetric water content values. This is the case because during the irrigation season the variation in soil moisture is reduced as percent of fine material in the soil increases. For sandy loam the field calibration showed extreme variation and for loam, silt loam, clay loam, and clay the field calibration resulted in a cluster of points located at the upper end of the volumetric content range.

The development of calibration equations from the field data resulted in mostly linear equations. The results for the field calibration are displayed in Table 2. The absolute error ranged from 3.6 to 318.8 % with an average absolute error of 43.3% for the 16 developed equations. The coefficient of determination varied between 0.106 and 0.964 with an average value of 0.678. The equations developed for sand collectively showed the lowest average absolute error of 7.62% with an average coefficient of determination of 0.884. The average absolute errors and coefficients of determination by soil texture for sandy loam, loam, and clay loam were 94.53% (0.692), 12.79% (0.677) and 51.41% (0.544) respectively. For silt loam and clay only one sample of the soil texture was collected and the absolute error and coefficient of determination for these was 70.21% (0.839) and 15.98% (0.222) respectively. The four fields with equations that exhibited the largest absolute error were Field 4 24" with 318.8%, Field 1 24" with 70.2%, Field 1 8" with 68.7", and Field 6 24" with 68.6%.

Laboratory Calibration

The data from the laboratory calibration showed much less scatter than the developed field calibration equations. The data from the lab calibration exhibited exclusively linear and polynomial relationships which covered a large range of volumetric water contents (Figure 4). The slope of the curvature for data points collected during the laboratory calibration was similar to the factory equation.

The laboratory calibrations were successfully for all 16 soils. The laboratory calibration allowed for precise management of bulk density and water content and therefore a large range of moisture contents was obtained for developing equations. For all 16 soil types the variation in obtained data was minimal which resulted in extremely accurate calibration equations.

The development of calibration equations from the laboratory data resulted in mostly polynomial equations. The results from the laboratory calibration effort are displayed in Table 3. The absolute error ranged from .053 to 3.13% with an average absolute error of 1.216% for the 16 developed equations. The coefficient of determination varied between 0.904 and 0.998 with an average value of 0.981. The equations developed for loam collectively showed the lowest average absolute error of 0.72% with an average coefficient of determination of 0.995. The average absolute errors and coefficients of determination by soil texture for sand, sandy loam, and clay loam were 1.44% (0.976), 1.15% (0.984) and 1.15% (0.988) respectively. For silt loam and clay only one sample of the soil texture was collected and the absolute error and coefficient of determination for these was 3.13% (0.904) and 1.06% (0.992) respectively. The four fields with equations that exhibited the largest absolute error were Field 1 24" with 3.13%, Field 3 8" with 1.94%, Field 5 24" with 1.73", and Field 8 24" with 1.71%.

Factory Equation

The standard factory equation resulted in significantly less error than the field calibration equations but more error than the laboratory calibration equations. Table 4 displays the results of applying the factory calibration equation.

The absolute error ranged from 3.17 to 10.41% with an average absolute error of 4.930% for the 16 soil samples. For loam the factory equation collectively showed the lowest average absolute error of 3.98% The average absolute errors by soil texture for sand, sandy loam, and clay loam were 4.94%, 6.94%, and 3.99%. For silt loam and clay only one sample of the soil texture was collected and the absolute error for these was 4.26% and 4.16% respectively. The four fields with equations that exhibited the largest absolute error were Field 7 24" with 10.41%, Field 4 24" with 7.00%, Field 8 8" with 6.73%", and Field 3 24" with 5.93%.

The factory equation on average under predicted for sand soil by 3.69% and 0.61% for sandy loam soils. For silt loam, loam, clay loam, and clay the factory on average over predicted the soil moisture content by 3.33, 2.86, 1.48, and 2.31% respectively.

Discussion

The results obtained during this study provide insight into the two calibration methods and the differences to the standard factory calibration equation. Field calibration of the EC-20 sensor is the least desired calibration method and exhibits the largest error rates. It was found that field calibration of the EC-20 sensor is limited due to heterogeneity in sampling locations, even though the sampling locations were adjacent to the EC-20 probe. Other limitations for field calibration which were observed during this study and by Kaleita et al (2005) were organic residues such as roots, worm holes, localized salinity, variations in field bulk density and the destructive and time consuming nature of the gravimetric sampling. The average r^2 values for the field calibration of 0.678 agree well with average values of 0.77, 0.69 and 0.74 obtained by Kaleita et al.

(2005), Polyakov et al. (2005), and Leib et al. (2003) for field calibrations. Although none of the fields exhibited an EC higher than 5.23 dS/m there is the possibility that the field calibrations were influenced by variations in salinity during the irrigation season and this issue merits further investigation. It was also found that probe failure in the field could have led to erroneous readings being correlated to a volumetric water content. On two occasions sensors failed due to water intrusion and gophers gnawing on the cables.

The error rates obtained using the field calibration method are extremely high and it would not be possible to accurately measure the amount of water added or depleted using the field calibration equations. Although we attempted to schedule field sampling to cover a wide range of moisture contents it was not possible to collect data at saturation or wilting point as farmers irrigated before this occurred. We therefore advise against using field calibrations for the EC-20 sensor and suggest performing the laboratory calibration presented here.

Our findings support that laboratory calibration is a highly accurate method to calibrate the EC-20 soil moisture sensor. The average r^2 value for the laboratory equations of 0.981 is significantly higher than the average r^2 value of 0.678 obtained from the field calibration. A high coefficient of determination indicates that the variability in the data is being explained adequately and our results for r^2 using the laboratory method compare favorably to the results of other researchers performing laboratory calibration equations for capacitance sensors. Kaleita et al, (2005) were able to obtain r^2 values of 0.85 and Polyakov et al. (2005) obtained values of 0.96 using laboratory calibration on capacitance sensors. The limited studies specific to the EC-20 have resulted in similar r^2

values with Nemali et al (2007) finding r^2 values of 0.95 for 9 soilless substrates. Using a similar sensor the ECH2O EC-5 Sakaki et al. (2008) were able to obtain r^2 values of 0.97.

The error rate observed indicates that the development of laboratory calibration equations can result in highly accurate measurement of soil moisture content. Our error rates agree well with Bosch, (2004) who found that using laboratory equations, error rates for the EC-10 and EC-20 in sandy coastal soil were $0.05 m^3/m^3$. Polyakov et al. (2005) found that the error rates were greatly reduced using laboratory calibrations in favor of field calibrations. Our findings also corroborate the results of Paltineanu and Starr, (1997) that the most accurate calibration is achieved in the laboratory.

The method of using a calibration cylinder results is highly accurate laboratory equations due to the ability to replicate field bulk density. The use of a single probe in the laboratory calibration to represent the behavior of other probes is also appropriate. Statistical analysis has shown that there that there is no significant difference in the measurements of individual ECH20 Probes (Kizito et al. 2008; Sakaki et al. (2008) Nemali et al. 2007), and therefore probe specific calibrations were not required. We recommend that laboratory calibrations of capacitance sensors be completed using the procedure outlined here as the management of field bulk density is crucial to developing accurate equations. In addition to ensuring accuracy the method replicates field conditions so that no distortion occurs and the developed equations can be applied to collected field data.

The results obtained during this study indicate that the factory equation accuracy is dependent on soil type. The underprediction of soil moisture content in sand and sandy loam soils we observed was also found by Plauborg et al. (2005) for a different capacitance sensor. In one of the few studies done using the EC-20 Bosch, (2004) found that the factory calibration equation consistently underpredicted the soil water content in three sandy coastal soils as well. For loam, silt loam, clay loam and clay the overprediction using the factory equation corresponds with results found by Inoue et al. (2008) and Polyakov et al. (2005). Both of these studies found that the manufacturer's equations overestimated the actual water content of dielectric soil moisture sensors. The fact that the factory equation underestimates for sandy soils and overestimates for loam and clay soils indicates that the equation is designed to be used for general applications and is not soil specific. Additionally, the factory equation is linear. We found that the behavior of the EC-20 probe in sandy soils was explained by a linear equation but that for loam, silt loam, clay loam, and clay the behavior was characterized by exponential curves. Although the factory equation is general we found that the accuracy of 4% without calibration suggested by the manufacturer was replicated in our study. Based on this finding we suggest using the factory calibration equation in studies where extremely low error rates are not required. For all other studies such as precision irrigation we recommend completing a laboratory calibration in favor of a field calibration due to the reasons mentioned previously.

During the installation of the EC-20 probes and the subsequent monitoring and data collection much information was gained that will be useful to other researchers using similar equipment. We found that the installation of the Em5B datalogger on a T-post should be carried out using wire and not the factory supplied zip ties. Due to the extreme sunlight present in New Mexico the zip ties were exposed to UV and became brittle and snapped in as little as two months. We also found that it was critical to use the factory supplied installation toolkit to ensure that sensors were not damaged during installation. Additionally, using the factory supplied auger was also crucial as the hole created is small and limits the amount of root damage. We recommend that the EC-20 sensors should be sealed at the interface between the probe and the lead wire with an extra layer of silicone before being installed to prevent water intrusion. If sensors are deployed away from the border of the field and longer cables are necessary we suggest purchasing the correct length already set from the factory. This eliminates having a wire junction buried in the field which leads to water instruction, electrical shorts, and erroneous sensor outputs. Finally, the sensors locations should be monitored and data downloaded continuously due to failure caused by gophers chewing on cables, other animals, and possible mechanical damage to dataloggers during normal field operations. Being diligent about monitoring the installation sites will prevent the loss of valuable data. One option that has recently become available for downloading data is the use of radio telementry and this offers the ability to remotely monitor installation sites. Although costly, this approach provides real time data that can be used for precise irrigation scheduling and warrants future study and implementation.

Conclusion

The study of the ECH2O EC-20 soil moisture probe in soils of the Middle Rio Grande Valley has shown that field calibration of the probe should be forgone for a laboratory calibration method. Through the completed study it was possible to develop 16 highly accurate lab calibration equations for the ECH2O EC-20 soil moisture sensor. The modified laboratory calibration method used in the equation development provides researchers with a method that manages the bulk density to replicate field conditions and develops highly accurate equations. It is our hope that the laboratory calibration method presented here assists researchers in obtaining more precise calibration equations. Additionally calibration equations for 16 EC-20 installations are presented which can be used by researchers in the Middle Rio Grande Valley and elsewhere where similar soil types exist.

Through the use of calibrated EC-20 soil moisture sensors it will become possible to precisely schedule irrigation events based on crop water requirements, which can reduce water use by up to 40% (Oad et al. 2009 ;Oad and Kullman, 2006). In the Middle Rio Grande this is extremely crucial. The use of these sensors offers the ability and opportunity to increase water use efficiency through irrigation scheduling and ensure the sustainability of agriculture in the Middle Rio Grande Valley as interstate compacts and ESA issues limit water available to agriculture during drought.

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Table 1: Soil Characteristics for Monitored Fields in the Middle Rio Grande Valley

Field	Depth (in)	% Sand (> .05mm)	% Silt (.002 to .05mm)	% Clay (< .002mm)	Field Bulk Density	Soil Class	pH	EC (ds/m)
3	24	90	5	5	1.594	Sand	7.80	4.29
5	24	96	2	2	1.518	Sand	7.93	3.14
8	24	96	2	2	1.597	Sand	7.58	2.89
3	8	76	14	10	1.54	Sandy Loam	7.79	3.07
4	24	78	16	6	1.68	Sandy Loam	8.07	2.00
7	24	60	29	11	1.511	Sandy Loam	7.75	2.90
8	8	67	19	14	1.478	Sandy Loam	6.95	1.73
1	24	23	52	25	1.617	Silt Loam	7.71	2.71
2	24	44	48.5	7.5	1.555	Loam	7.85	4.39
4	8	43	31	26	1.467	Loam	7.62	3.80
5	8	36	48	16	1.369	Loam	7.41	6.29
7	8	43	35	22	1.544	Loam	7.72	3.20
1	8	40	27.5	32.5	1.420	Clay Loam	8.03	3.51
6	8	23	50	27	1.474	Clay Loam	7.75	4.00
6	24	23	47	30	1.522	Clay Loam	7.87	3.60
2	8	20	27.5	52.5	1.406	Clay	7.85	5.23

Table 2: Results of Field Calibration for EC-20 Soil Moisture Sensor

Field	Depth (in)	Soil Class	Field Equation	Field r2	Range in volumetric Water Content Field	Abs Error Field %
3	24	Sand	7.68E-04x - 5.52E-01	0.908	0.09-0.29	5.8349
5	24	Sand	6.26E-04x - 4.98E-01	0.964	0.08-0.32	6.0877
8	24	Sand	7.06E-04x - 5.32E-01	0.781	0.10 -0.40	10.9476
3	8	Sandy Loam	1.05E-06x2 - 2.24E-03x + 1.32E+00	0.798	0.11-0.23	7.8253
4	24	Sandy Loam	7.46E-03x - 9.84E+00	0.918	0.06-0.35	318.8346
7	24	Sandy Loam	1.01E-04x + 1.59E-01	0.163	0.09-0.29	25.5470
8	8	Sandy Loam	2.37E-04x - 3.73E-03	0.890	0.23 -0.30	25.9222
1	24	Silt Loam	2.19E-03x - 3.13E+00	0.839	0.33-0.40	70.2113
2	24	Loam	7.70E-04x - 6.90E-01	0.903	0.40-0.44	12.7251
4	8	Loam	7.44E-05x + 3.10E-01	0.106	0.21-0.34	21.5893
5	8	Loam	7.81E-04x - 8.30E-01	0.779	0.25-0.40	13.2256
7	8	Loam	3.15E-04x - 1.60E-01	0.920	0.19-0.33	3.6245
1	8	Clay Loam	1.71E-03x - 2.38E+00	0.760	0.26-0.37	68.6904
6	8	Clay Loam	1.13E-03x - 1.29E+00	0.249	0.35-0.46	16.9220
6	24	Clay Loam	2.85E-03x - 3.86E+00	0.652	0.37-0.45	68.6280
2	8	Clay	1.93E-04x + 1.28E-01	0.222	0.41-0.44	15.9809

Table 3: Results of Laboratory Calibration for EC-20 Soil Moisture Sensor

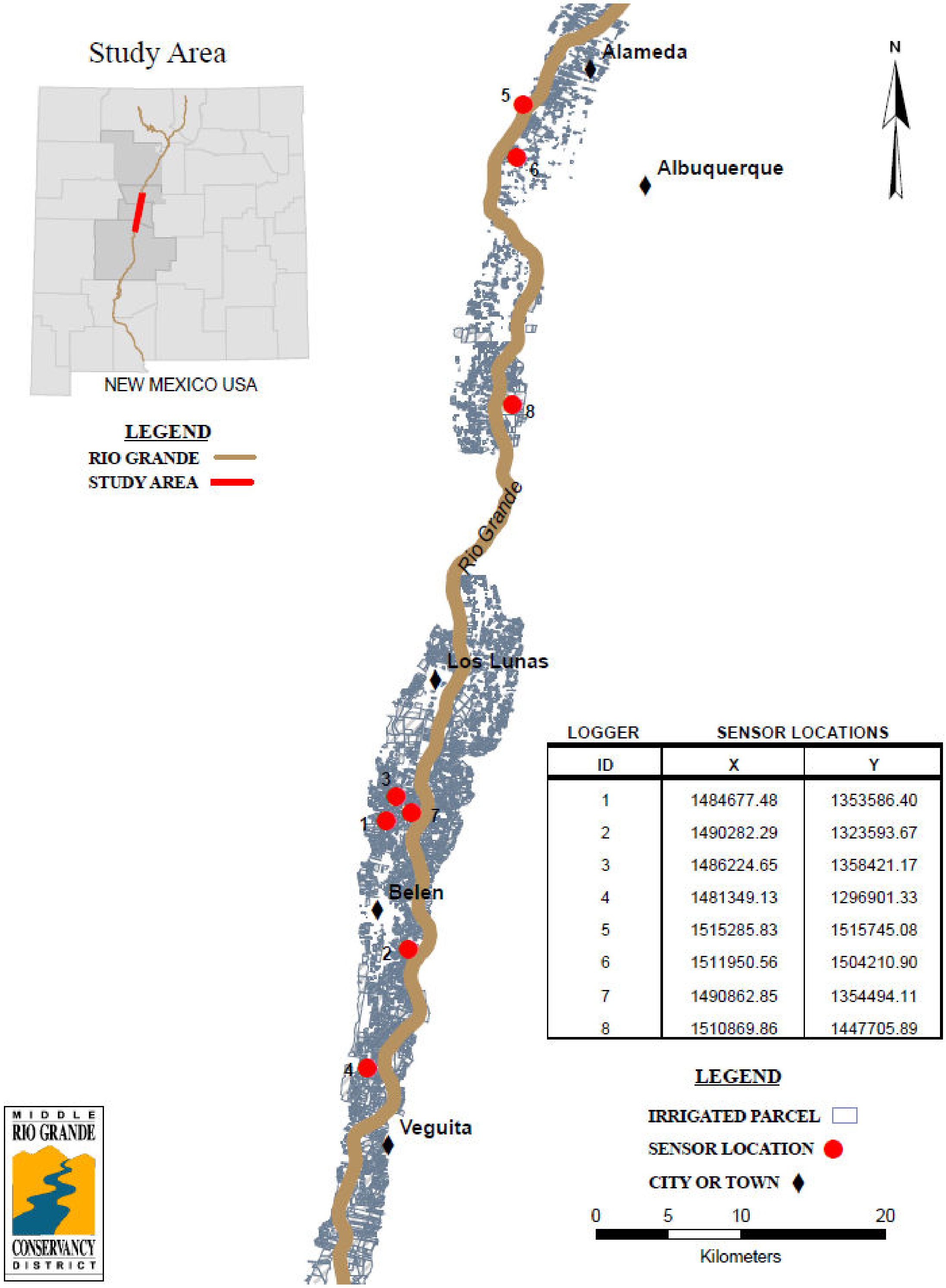
Field	Depth (in)	Soil Class	Laboratory Equation	Laboratory r2	Range in Volumetric Water Content	Abs Error Laboratory %
3	24	Sand	4.97E-04x - 3.04E-01	0.992	0.004-0.36	0.8811
5	24	Sand	4.14E-04x - 2.73E-01	0.950	0.004-0.34	1.7313
8	24	Sand	4.38E-04x - 2.73E-01	0.986	0.004-0.30	1.7068
3	8	Sandy Loam	5.23E-07x2 - 7.51E-04x + 2.97E-01	0.962	0.008 - 0.41	1.9379
4	24	Sandy Loam	-8.72E-09x2 + 5.21E-04x - 3.01E-01	0.995	0.02-0.33	0.5766
7	24	Sandy Loam	2.17E-07x2 - 7.98E-05x - 2.44E-02	0.987	0.002-0.31	1.1109
8	8	Sandy Loam	2.30E-07x2 - 1.31E-04x + 1.58E-03	0.991	0.004-0.38	0.9568
1	24	Silt Loam	4.13E-04x - 3.10E-01	0.904	0.004-0.38	3.1318
2	24	Loam	4.57E-07x2 - 6.31E-04x + 2.40E-01	0.991	0.004-0.37	1.0766
4	8	Loam	1.73E-07x2 - 3.05E-05x - 4.42E-02	0.994	0.002-0.36	0.6695
5	8	Loam	1.43E-07x2 + 3.21E-05x - 7.47E-02	0.998	0.008-0.44	0.5309
7	8	Loam	1.87E-07x2 - 4.27E-05x - 4.59E-02	0.996	0.004-0.37	0.6250
1	8	Clay Loam	2.99E-07x2 - 1.60E-04x - 1.73E-02	0.982	0.008-0.40	1.4866
6	8	Clay Loam	3.88E-07x2 - 4.58E-04x + 1.42E-01	0.991	0.006-0.41	0.8041
6	24	Clay Loam	5.05E-07x2 - 7.12E-04x + 2.65E-01	0.991	0.008-0.41	1.1669
2	8	Clay	4.49E-07x2 - 6.21E-04x + 2.48E-01	0.992	0.03-0.45	1.0591

Table 4: Results of Factory Calibration Equation for EC-20 Soil Moisture Sensor

Field	Depth (in)	Soil Class	Abs Error Factory %
3	24	Sand	5.9302
5	24	Sand	4.4317
8	24	Sand	4.4558
3	8	Sandy Loam	3.6185
4	24	Sandy Loam	7.0032
7	24	Sandy Loam	10.4127
8	8	Sandy Loam	6.7334
1	24	Silt Loam	4.2555
2	24	Loam	4.4791
4	8	Loam	3.8873
5	8	Loam	4.0910
7	8	Loam	3.4575
1	8	Clay Loam	3.1754
6	8	Clay Loam	4.4102
6	24	Clay Loam	4.3898
2	8	Clay	4.1558

Figure 1

Figure 2



LOGGER ID	SENSOR LOCATIONS X	SENSOR LOCATIONS Y
1	1484677.48	1353586.40
2	1490282.29	1323593.67
3	1486224.65	1358421.17
4	1481349.13	1296901.33
5	1515285.83	1515745.08
6	1511950.56	1504210.90
7	1490862.85	1354494.11
8	1510869.86	1447705.89

Figure 3

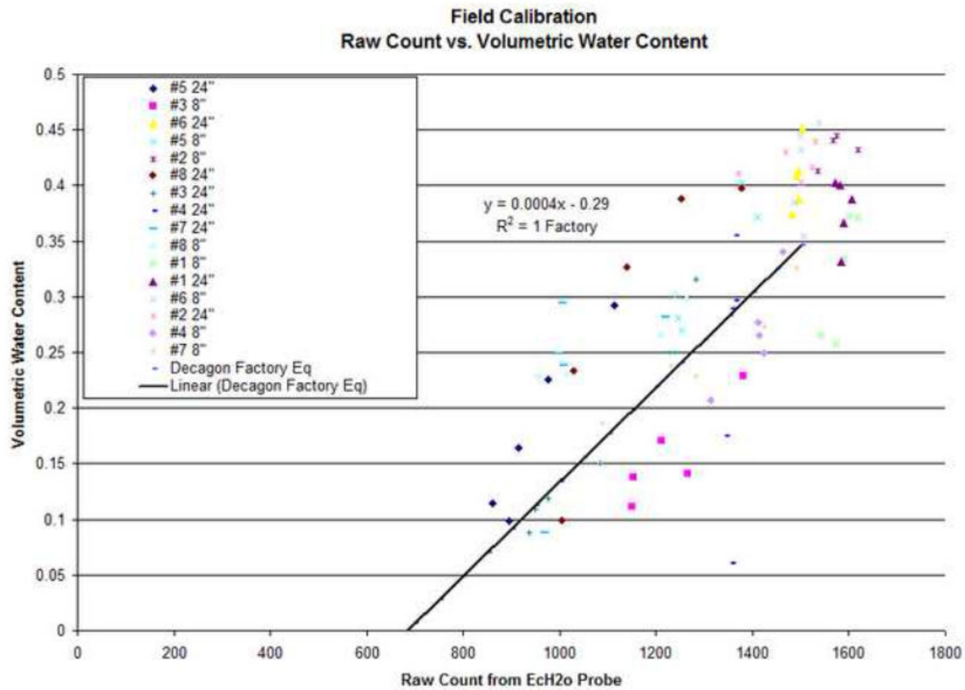
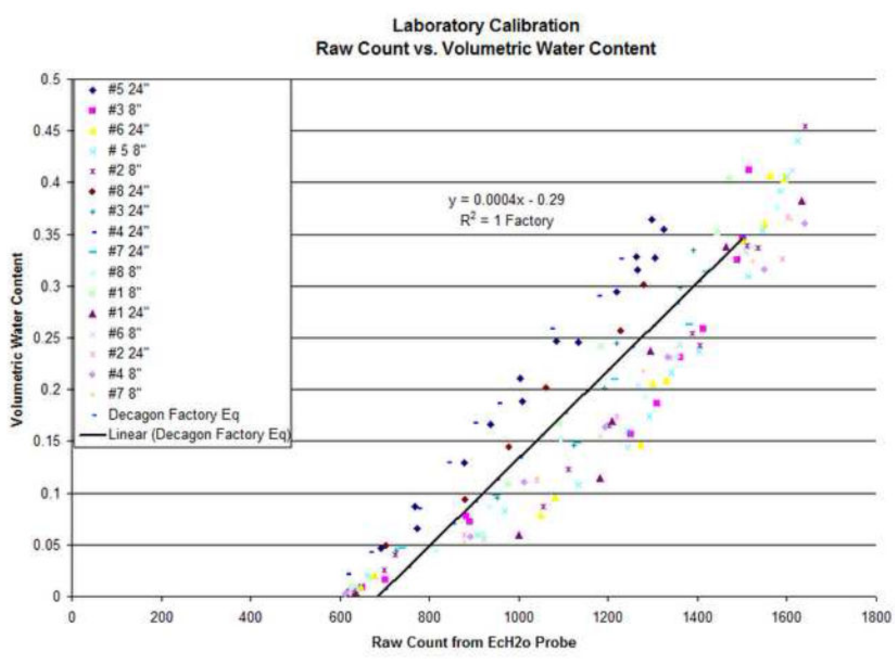


Figure 4



APPENDIX I: DEPTH APPLIED PER IRRIGATION DATA FOR THE EIGHT INSTRUMENTED FIELDS FOR THE 2008 AND 2009 IRRIGATION SEASONS

Logger ID	Irrigation Event	Date	Total Water Applied (ft^3)	Depth Applied (inches)
1	1	4/14/2008	157190	6.95
1	2	5/5/2008	266004	7.44
1	3	6/1/2008	325216	9.09
1	4	6/24/2008	149748	4.19
1	5	8/6/2008	150338	4.2
1	6	9/12/2008	125121	3.5
1	1	4/13/2009	112475	3.15
1	2	5/11/2009	148812	4.16
1	3	6/18/2009	173791	4.86
1	4	7/20/2009	113443	3.17
1	5	8/27/2009	130644	3.65
2	1	4/5/2008	235170	5.14
2	2	4/25/2008	275952	6.03
2	3	5/23/2008	341320	7.46
2	4	6/20/2008	387476	8.46
2	5	7/3/2008	296378	6.47
2	6	8/6/2008	171854	3.75
2	7	8/28/2008	324088	7.08
2	8	9/12/2008	357262	7.8
2	1	3/31/2009	480247	10.49
2	2	4/30/2009	240987	5.26
2	3	6/6/2009	371979	8.13
2	4	7/11/2009	416958	9.11
2	5	7/23/2009	332587	7.27
2	6	8/21/2009	421457	9.21
3	1	5/2/2008	125775	3.21
3	2	5/23/2008	217299	5.55
3	3	6/19/2008	200079	5.11
3	4	8/1/2008	238567	6.1
3	5	9/4/2008	135483	3.46
3	6	9/24/2008	151377	3.87
3	1	4/23/2009	152564	3.9
3	2	5/11/2009	269414	6.88
3	3	6/4/2009	177247	4.53
3	4	7/13/2009	221764	5.67
3	5	7/29/2009	165790	4.24
3	6	9/3/2009	190490	4.87
3	7	10/15/2009	272789	6.97
4	1	4/19/2008	49920	3.13
4	2	5/5/2008	36504	2.29

Logger ID	Irrigation Event	Date	Total Water Applied (ft^3)	Depth Applied (inches)
4	3	5/23/2008	74667	4.67
4	4	6/7/2008	94543	5.92
4	5	6/27/2008	77265	4.84
4	6	7/9/2008	82913	5.19
4	7	8/6/2008	105161	6.58
4	8	8/20/2008	80683	5.05
4	9	9/10/2008	71934	4.5
4	10	9/23/2008	65226	4.08
4	11	10/30/2008	90905	5.69
4	1	3/10/2009	102177	6.4
4	2	4/11/2009	92362	5.78
4	3	4/22/2009	61405	3.84
4	4	5/9/2009	90539	5.67
4	5	5/26/2009	85127	5.33
4	6	6/9/2009	80272	5.03
4	7	7/6/2009	81828	5.12
4	8	7/22/2009	87585	5.48
4	9	8/10/2009	34582	2.17
4	10	9/2/2009	100781	6.31
4	11	9/17/2009	76073	4.76
5	1	4/17/2008	76284	5.75
5	2	5/1/2008	63900	4.82
5	3	5/15/2008	65538	4.94
5	4	5/29/2008	46299	3.49
5	5	6/12/2008	56623	4.27
5	6	6/26/2008	60617	4.57
5	7	7/10/2008	64076	4.83
5	8	7/25/2008	91283	6.88
5	9	8/7/2008	56162	4.23
5	10	8/21/2008	74721	5.63
5	11	9/4/2008	98884	7.45
5	12	9/18/2008	74384	5.61
5	13	10/2/2008	64293	4.85
5	14	10/23/2008	46842	3.53
5	1	3/26/2009	37912	2.86
5	2	4/16/2009	34191	2.58
5	3	5/7/2009	37670	2.84
5	4	5/23/2009	75344	5.68
5	5	6/5/2009	58230	4.39
5	6	6/18/2009	77990	5.88

Logger ID	Irrigation Event	Date	Total Water Applied (ft^3)	Depth Applied (inches)
5	7	7/2/2009	55002	4.15
5	8	7/16/2009	101087	7.62
5	9	7/30/2009	84503	6.37
5	10	8/13/2009	107675	8.12
5	11	9/3/2009	117865	8.88
5	12	9/24/2009	60919	4.59
5	13	10/16/2009	78388	5.91
5	14	10/29/2009	39767	3
6	1	4/22/2008	101402	5.16
6	2	5/15/2008	76917	3.91
6	3	5/30/2008	68859	3.5
6	4	6/12/2008	44546	2.27
6	5	6/26/2008	40097	2.04
6	6	7/10/2008	45518	2.31
6	7	7/27/2008	32135	1.63
6	8	8/7/2008	76505	3.89
6	9	8/26/2008	130465	6.63
6	10	9/11/2008	109373	5.56
6	11	10/3/2008	162258	8.25
6	1	3/31/2009	198449	6.1
6	2	4/18/2009	126398	3.88
6	3	4/29/2009	201808	6.2
6	4	5/12/2009	186066	5.72
6	5	6/4/2009	210639	6.47
6	6	6/17/2009	111214	3.42
6	7	7/2/2009	133732	4.11
6	8	7/20/2009	179173	5.51
6	9	8/6/2009	159831	4.91
6	10	8/20/2009	173397	5.33
6	11	9/8/2009	175579	5.39
6	12	10/2/2009	188051	5.78
7	1	4/25/2008	40770	2.5
7	2	5/9/2008	97481	5.99
7	3	6/1/2008	70967	4.36
7	4	6/23/2008	123476	7.58
7	5	7/13/2008	91389	5.61
7	6	8/8/2008	112546	6.91
7	7	9/5/2008	101239	6.22
7	8	9/21/2008	74809	4.59
7	1	4/10/2009	85990	5.28

Logger ID	Irrigation Event	Date	Total Water Applied (ft^3)	Depth Applied (inches)
7	2	4/27/2009	73584	4.52
7	3	5/15/2009	94796	5.82
7	4	6/9/2009	96963	5.96
7	5	7/17/2009	128516	7.89
7	6	8/21/2009	154389	9.48
7	7	9/3/2009	124178	7.63
7	8	10/4/2009	49532	3.04
8	2	5/24/2008	261003	13.68
8	3	6/6/2008	325899	11.1
8	4	7/1/2008	196965	10.32
8	5	7/19/2008	192629	6.56
8	6	8/3/2008	181595	9.52
8	7	8/28/2008	263721	8.98
8	8	9/19/2008	229606	7.82
8	1	3/16/2009	147697	5.03
8	2	4/2/2009	235892	8.03
8	3	4/25/2009	290761	9.9
8	4	6/2/2009	286696	9.76
8	5	6/21/2009	183570	6.25
8	6	7/4/2009	227981	7.76
8	7	7/24/2009	223510	7.61
8	8	8/13/2009	230864	7.86
8	9	9/10/2009	367125	12.5
8	10	10/6/2009	251818	8.58

APPENDIX J: APPLICATION EFFICIENCY DATA FOR THE EIGHT INSTRUMENTED FIELDS FOR THE 2008 AND 2009 IRRIGATION SEASONS

Logger ID	Irrigation Event	Date	Depth Applied (inches)	Moisture Applied for Crop Use (inches)	Application Efficiency (%)
1	1	4/14/2008	6.95	4.64	67%
1	2	5/5/2008	7.44	1.92	26%
1	3	6/1/2008	9.09	3.36	37%
1	4	6/24/2008	4.19	2.24	53%
1	5	8/6/2008	4.2	1.76	42%
1	6	9/12/2008	3.5	2.4	69%
1	1	4/13/2009	3.15	2.56	81%
1	2	5/11/2009	4.16	2.56	62%
1	3	6/18/2009	4.86	2.56	53%
1	4	7/20/2009	3.17	1.12	35%
1	5	8/27/2009	3.65	3.68	100%
2	1	4/5/2008	5.14	4.16	81%
2	2	4/25/2008	6.03	1.76	29%
2	3	5/23/2008	7.46	1.76	24%
2	4	6/20/2008	8.46	2.4	28%
2	5	7/3/2008	6.47	1.28	20%
2	6	8/6/2008	3.75	0.96	26%
2	7	8/28/2008	7.08	0.96	14%
2	8	9/12/2008	7.8	1.12	14%
2	1	3/31/2009	10.49	2.4	23%
2	2	4/30/2009	5.26	0.96	18%
2	3	6/6/2009	8.13	1.28	16%
2	4	7/11/2009	9.11	2.56	28%
2	5	7/23/2009	7.27	1.92	26%
2	6	8/21/2009	9.21	2.4	26%
3	1	5/2/2008	3.21	4.8	100%
3	2	5/23/2008	5.55	2.88	52%
3	3	6/19/2008	5.11	4	78%
3	4	8/1/2008	6.1	5.92	97%
3	5	9/4/2008	3.46	5.12	100%
3	6	9/24/2008	3.87	2.56	66%
3	1	4/23/2009	3.9	8	100%
3	2	5/11/2009	6.88	3.68	53%
3	3	6/4/2009	4.53	4.96	100%
3	4	7/13/2009	5.67	6.56	100%
3	5	7/29/2009	4.24	3.84	91%
3	6	9/3/2009	4.87	5.12	100%
3	7	10/15/2009	6.97	3.52	50%
4	1	4/19/2008	3.13	2.4	77%

Logger ID	Irrigation Event	Date	Depth Applied (inches)	Moisture Applied for Crop Use (inches)	Application Efficiency (%)
4	2	5/5/2008	2.29	2.44	100%
4	3	5/23/2008	4.67	2.6	56%
4	4	6/7/2008	5.92	2.2	37%
4	5	6/27/2008	4.84	2.84	59%
4	6	7/9/2008	5.19	1.4	27%
4	7	8/6/2008	6.58	2.84	43%
4	8	8/20/2008	5.05	1.88	37%
4	9	9/10/2008	4.5	2.36	52%
4	10	9/23/2008	4.08	1.2	29%
4	11	10/30/2008	5.69	1.88	33%
4	1	3/10/2009	6.4	3.96	62%
4	2	4/11/2009	5.78	2.56	44%
4	3	4/22/2009	3.84	1.36	35%
4	4	5/9/2009	5.67	2.64	47%
4	5	5/26/2009	5.33	2.68	50%
4	6	6/9/2009	5.03	2.36	47%
4	7	7/6/2009	5.12	3.44	67%
4	8	7/22/2009	5.48	2.52	46%
4	9	8/10/2009	2.17	3.44	100%
4	10	9/2/2009	6.31	3.16	50%
4	11	9/17/2009	4.76	1.32	28%
5	1	4/17/2008	5.75	1.76	31%
5	2	5/1/2008	4.82	1.64	34%
5	3	5/15/2008	4.94	2.8	57%
5	4	5/29/2008	3.49	2.76	79%
5	5	6/12/2008	4.27	2.12	50%
5	6	6/26/2008	4.57	1.52	33%
5	7	7/10/2008	4.83	2.2	46%
5	8	7/25/2008	6.88	2.56	37%
5	9	8/7/2008	4.23	1.32	31%
5	10	8/21/2008	5.63	2.2	39%
5	11	9/4/2008	7.45	2.72	36%
5	12	9/18/2008	5.61	2.4	43%
5	13	10/2/2008	4.85	2.08	43%
5	14	10/23/2008	3.53	1.4	40%
5	1	3/26/2009	2.86	2.32	81%
5	2	4/16/2009	2.58	0.88	34%
5	3	5/7/2009	2.84	3.16	100%
5	4	5/23/2009	5.68	2.96	52%
5	5	6/5/2009	4.39	1.64	37%

Logger ID	Irrigation Event	Date	Depth Applied (inches)	Moisture Applied for Crop Use (inches)	Application Efficiency (%)
5	6	6/18/2009	5.88	1.56	27%
5	7	7/2/2009	4.15	2.24	54%
5	8	7/16/2009	7.62	2.52	33%
5	9	7/30/2009	6.37	0.92	14%
5	10	8/13/2009	8.12	2.92	36%
5	11	9/3/2009	8.88	3.56	40%
5	12	9/24/2009	4.59	0.72	16%
5	13	10/16/2009	5.91	1.48	25%
5	14	10/29/2009	3	0.72	24%
6	1	4/22/2008	5.16	1.92	37%
6	2	5/15/2008	3.91	1.28	33%
6	3	5/30/2008	3.5	1.44	41%
6	4	6/12/2008	2.27	1.44	64%
6	5	6/26/2008	2.04	1.44	71%
6	6	7/10/2008	2.31	1.44	62%
6	7	7/27/2008	1.63	1.44	88%
6	8	8/7/2008	3.89	1.6	41%
6	9	8/26/2008	6.63	1.44	22%
6	10	9/11/2008	5.56	1.44	26%
6	11	10/3/2008	8.25	1.28	16%
6	1	3/31/2009	6.1	2.4	39%
6	2	4/18/2009	3.88	1.28	33%
6	3	4/29/2009	6.2	1.12	18%
6	4	5/12/2009	5.72	1.28	22%
6	5	6/4/2009	6.47	1.44	22%
6	6	6/17/2009	3.42	2.24	66%
6	7	7/2/2009	4.11	2.4	58%
6	8	7/20/2009	5.51	2.72	49%
6	9	8/6/2009	4.91	3.52	72%
6	10	8/20/2009	5.33	3.04	57%
6	11	9/8/2009	5.39	1.92	36%
6	12	10/2/2009	5.78	2.24	39%
7	1	4/25/2008	2.5	2.08	83%
7	2	5/9/2008	5.99	1.24	21%
7	3	6/1/2008	4.36	1.6	37%
7	4	6/23/2008	7.58	1.92	25%
7	5	7/13/2008	5.61	1.04	19%
7	6	8/8/2008	6.91	2.04	30%
7	7	9/5/2008	6.22	1.72	28%
7	8	9/21/2008	4.59	1.2	26%

Logger ID	Irrigation Event	Date	Depth Applied (inches)	Moisture Applied for Crop Use (inches)	Application Efficiency (%)
7	1	4/10/2009	5.28	4.56	86%
7	2	4/27/2009	4.52	0.72	16%
7	3	5/15/2009	5.82	1.2	21%
7	4	6/9/2009	5.96	2	34%
7	5	7/17/2009	7.89	3.68	47%
7	6	8/21/2009	9.48	3.12	33%
7	7	9/3/2009	7.63	1.04	14%
7	8	10/4/2009	3.04	1.2	39%
8	2	5/24/2008	13.68	4.92	36%
8	3	6/6/2008	11.1	3.72	34%
8	4	7/1/2008	10.32	3.88	38%
8	5	7/19/2008	6.56	3.76	57%
8	6	8/3/2008	9.52	2.08	22%
8	7	8/28/2008	8.98	1.6	18%
8	8	9/19/2008	7.82	0.88	11%
8	1	3/16/2009	5.03	0.84	17%
8	2	4/2/2009	8.03	0.72	9%
8	3	4/25/2009	9.9	1.2	12%
8	4	6/2/2009	9.76	2.52	26%
8	5	6/21/2009	6.25	2.68	43%
8	6	7/4/2009	7.76	3.24	42%
8	7	7/24/2009	7.61	1.96	26%
8	8	8/13/2009	7.86	1.96	25%
8	9	9/10/2009	12.5	1.76	14%
8	10	10/6/2009	8.58	0.72	8%

APPENDIX K: MANAGEMENT ALLOWED DEPLETION (MAD) DATA FOR THE EIGHT INSTRUMENTED FIELDS FOR THE 2008 AND 2009 IRRIGATION SEASONS

Logger ID	Irrigation Event	Date	MAD
1	1	4/14/2008	0.6
1	2	5/5/2008	0.24
1	3	6/1/2008	0.45
1	4	6/24/2008	0.29
1	5	8/6/2008	0.2
1	6	9/12/2008	0.29
1	1	4/13/2009	0.26
1	2	5/11/2009	0.29
1	3	6/18/2009	0.28
1	4	7/20/2009	0.13
1	5	8/27/2009	0.44
2	1	4/5/2008	0.99
2	2	4/25/2008	0.35
2	3	5/23/2008	0.34
2	4	6/20/2008	0.48
2	5	7/3/2008	0.26
2	6	8/6/2008	0.11
2	7	8/28/2008	0.11
2	8	9/12/2008	0.13
2	1	3/31/2009	0.32
2	2	4/30/2009	0.12
2	3	6/6/2009	0.15
2	4	7/11/2009	0.28
2	5	7/23/2009	0.21
2	6	8/21/2009	0.28
3	1	5/2/2008	0.57
3	2	5/23/2008	0.38
3	3	6/19/2008	0.5
3	4	8/1/2008	0.61
3	5	9/4/2008	0.49
3	6	9/24/2008	0.23
3	1	4/23/2009	0.74
3	2	5/11/2009	0.34
3	3	6/4/2009	0.45
3	4	7/13/2009	0.57
3	5	7/29/2009	0.32
3	6	9/3/2009	0.45
3	7	10/15/2009	0.34
4	1	4/19/2008	0.23
4	2	5/5/2008	0.22
4	3	5/23/2008	0.22

Logger ID	Irrigation Event	Date	MAD
4	4	6/7/2008	0.19
4	5	6/27/2008	0.23
4	6	7/9/2008	0.12
4	7	8/6/2008	0.23
4	8	8/20/2008	0.15
4	9	9/10/2008	0.2
4	10	9/23/2008	0.1
4	11	10/30/2008	0.17
4	1	3/10/2009	0.34
4	2	4/11/2009	0.23
4	3	4/22/2009	0.12
4	4	5/9/2009	0.24
4	5	5/26/2009	0.24
4	6	6/9/2009	0.2
4	7	7/6/2009	0.3
4	8	7/22/2009	0.21
4	9	8/10/2009	0.29
4	10	9/2/2009	0.26
4	11	9/17/2009	0.11
5	1	4/17/2008	0.51
5	2	5/1/2008	0.41
5	3	5/15/2008	0.54
5	4	5/29/2008	0.53
5	5	6/12/2008	0.46
5	6	6/26/2008	0.38
5	7	7/10/2008	0.62
5	8	7/25/2008	0.72
5	9	8/7/2008	0.47
5	10	8/21/2008	0.73
5	11	9/4/2008	0.97
5	12	9/18/2008	0.7
5	13	10/2/2008	0.74
5	14	10/23/2008	0.61
5	1	3/26/2009	1
5	2	4/16/2009	0.38
5	3	5/7/2009	0.74
5	4	5/23/2009	0.67
5	5	6/5/2009	0.39
5	6	6/18/2009	0.45
5	7	7/2/2009	0.66
5	8	7/16/2009	0.88
5	9	7/30/2009	0.39

Logger ID	Irrigation Event	Date	MAD
5	10	8/13/2009	1
5	11	9/3/2009	1
5	12	9/24/2009	0.34
5	13	10/16/2009	0.77
6	1	4/22/2008	0.29
6	2	5/15/2008	0.19
6	3	5/30/2008	0.19
6	4	6/12/2008	0.19
6	5	6/26/2008	0.19
6	6	7/10/2008	0.18
6	7	7/27/2008	0.18
6	8	8/7/2008	0.2
6	9	8/26/2008	0.18
6	10	9/11/2008	0.18
6	11	10/3/2008	0.16
6	1	3/31/2009	0.49
6	2	4/18/2009	0.27
6	3	4/29/2009	0.24
6	4	5/12/2009	0.26
6	5	6/4/2009	0.28
6	6	6/17/2009	0.44
6	7	7/2/2009	0.45
6	8	7/20/2009	0.52
6	9	8/6/2009	0.67
6	10	8/20/2009	0.6
6	11	9/8/2009	0.42
6	12	10/2/2009	0.52
7	1	4/25/2008	0.73
7	2	5/9/2008	0.43
7	3	6/1/2008	0.56
7	4	6/23/2008	0.67
7	5	7/13/2008	0.34
7	6	8/8/2008	0.47
7	7	9/5/2008	0.42
7	8	9/21/2008	0.28
7	1	4/10/2009	0.96
7	2	4/27/2009	0.14
7	3	5/15/2009	0.21
7	4	6/9/2009	0.35
7	5	7/17/2009	0.62
7	6	8/21/2009	0.52
7	7	9/3/2009	0.17

Logger ID	Irrigation Event	Date	MAD
7	8	10/4/2009	0.21
8	2	5/24/2008	0.65
8	3	6/6/2008	0.45
8	4	7/1/2008	0.46
8	5	7/19/2008	0.41
8	6	8/3/2008	0.23
8	7	8/28/2008	0.25
8	8	9/19/2008	0.16
8	1	3/16/2009	0.23
8	2	4/2/2009	0.18
8	3	4/25/2009	0.25
8	4	6/2/2009	0.37
8	5	6/21/2009	0.34
8	6	7/4/2009	0.35
8	7	7/24/2009	0.22
8	8	8/13/2009	0.25
8	9	9/10/2009	0.26
8	10	10/6/2009	0.14

APPENDIX L: % RAM REMAINING DATA FOR THE EIGHT INSTRUMENTED FIELDS FOR THE 2008 AND 2009 IRRIGATION SEASONS

Logger ID	Irrigation Event	Date	% RAM Remaining
1	1	4/14/2008	0%
1	2	5/5/2008	26%
1	3	6/1/2008	0%
1	4	6/24/2008	13%
1	5	8/6/2008	39%
1	6	9/12/2008	13%
1	1	4/13/2009	21%
1	2	5/11/2009	12%
1	3	6/18/2009	16%
1	4	7/20/2009	61%
1	5	8/27/2009	0%
2	1	4/5/2008	0%
2	2	4/25/2008	0%
2	3	5/23/2008	0%
2	4	6/20/2008	0%
2	5	7/3/2008	22%
2	6	8/6/2008	66%
2	7	8/28/2008	66%
2	8	9/12/2008	61%
2	1	3/31/2009	2%
2	2	4/30/2009	64%
2	3	6/6/2009	55%
2	4	7/11/2009	14%
2	5	7/23/2009	36%
2	6	8/21/2009	53%
3	1	5/2/2008	0%
3	2	5/23/2008	0%
3	3	6/19/2008	0%
3	4	8/1/2008	0%
3	5	9/4/2008	0%
3	6	9/24/2008	31%
3	1	4/23/2009	0%
3	2	5/11/2009	0%
3	3	6/4/2009	0%
3	4	7/13/2009	0%
3	5	7/29/2009	4%
3	6	9/3/2009	0%
3	7	10/15/2009	43%
4	1	4/19/2008	45%
4	2	5/5/2008	46%
4	3	5/23/2008	46%
4	4	6/7/2008	53%

Logger ID	Irrigation Event	Date	% RAM Remaining
4	5	6/27/2008	43%
4	6	7/9/2008	71%
4	7	8/6/2008	43%
4	8	8/20/2008	63%
4	9	9/10/2008	51%
4	10	9/23/2008	75%
4	11	10/30/2008	59%
4	1	3/10/2009	18%
4	2	4/11/2009	44%
4	3	4/22/2009	71%
4	4	5/9/2009	42%
4	5	5/26/2009	43%
4	6	6/9/2009	52%
4	7	7/6/2009	26%
4	8	7/22/2009	48%
4	9	8/10/2009	30%
4	10	9/2/2009	35%
4	11	9/17/2009	81%
5	1	4/17/2008	0%
5	2	5/1/2008	1%
5	3	5/15/2008	0%
5	4	5/29/2008	0%
5	5	6/12/2008	0%
5	6	6/26/2008	6%
5	7	7/10/2008	0%
5	8	7/25/2008	0%
5	9	8/7/2008	0%
5	10	8/21/2008	0%
5	11	9/4/2008	0%
5	12	9/18/2008	0%
5	13	10/2/2008	0%
5	14	10/23/2008	0%
5	1	3/26/2009	0%
5	2	4/16/2009	7%
5	3	5/7/2009	0%
5	4	5/23/2009	0%
5	5	6/5/2009	6%
5	6	6/18/2009	0%
5	7	7/2/2009	0%
5	8	7/16/2009	0%
5	9	7/30/2009	5%
5	10	8/13/2009	0%

Logger ID	Irrigation Event	Date	% RAM Remaining
5	11	9/3/2009	0%
5	12	9/24/2009	44%
5	13	10/16/2009	0%
5	14	10/29/2009	38%
6	1	4/22/2008	11%
6	2	5/15/2008	43%
6	3	5/30/2008	42%
6	4	6/12/2008	42%
6	5	6/26/2008	42%
6	6	7/10/2008	45%
6	7	7/27/2008	45%
6	8	8/7/2008	40%
6	9	8/26/2008	46%
6	10	9/11/2008	45%
6	11	10/3/2008	50%
6	1	3/31/2009	0%
6	2	4/18/2009	18%
6	3	4/29/2009	29%
6	4	5/12/2009	21%
6	5	6/4/2009	17%
6	6	6/17/2009	0%
6	7	7/2/2009	0%
6	8	7/20/2009	0%
6	9	8/6/2009	0%
6	10	8/20/2009	0%
6	11	9/8/2009	31%
6	12	10/2/2009	13%
7	1	4/25/2008	0%
7	2	5/9/2008	0%
7	3	6/1/2008	0%
7	4	6/23/2008	0%
7	5	7/13/2008	16%
7	6	8/8/2008	0%
7	7	9/5/2008	0%
7	8	9/21/2008	32%
7	1	4/10/2009	0%
7	2	4/27/2009	67%
7	3	5/15/2009	49%
7	4	6/9/2009	15%
7	5	7/17/2009	0%
7	6	8/21/2009	0%
7	7	9/3/2009	57%

Logger ID	Irrigation Event	Date	% RAM Remaining
7	8	10/4/2009	65%
8	2	5/24/2008	0%
8	3	6/6/2008	0%
8	4	7/1/2008	0%
8	5	7/19/2008	0%
8	6	8/3/2008	44%
8	7	8/28/2008	38%
8	8	9/19/2008	62%
8	1	3/16/2009	45%
8	2	4/2/2009	55%
8	3	4/25/2009	38%
8	4	6/2/2009	9%
8	5	6/21/2009	18%
8	6	7/4/2009	15%
8	7	7/24/2009	47%
8	8	8/13/2009	59%
8	9	9/10/2009	58%
8	10	10/6/2009	77%

APPENDIX M: KINZLI, MARTINEZ, OAD, PRIOR AND GENSLER (2010)

USING AN ADCP TO DETERMINE CANAL SEEPAGE IN AN IRRIGATION DISTRICT

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Using an ADCP to determine canal seepage loss in an irrigation district

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ABSTRACT

Seepage from earthen irrigation canals represents substantial water loss in irrigation districts. Historically, the determination of canal seepage was accomplished using the inflow–outflow method with propeller and electromagnetic type flow meters. This method was difficult, time consuming, and limited by measurement device accuracy. In recent years, advances in technology have lead to the widespread use of Acoustic Doppler Current Profilers (ADCP) for discharge measurements in streams and rivers. Even though ADCP use has become widespread for stream discharges, studies to determine canal seepage using this new technology are limited. Using an ADCP, extensive field measurements were conducted in the Middle Rio Grande Conservancy District. This paper describes the ADCP measurement protocol used to measure irrigation canal seepage and presents predictive equations for determining canal seepage based on flow rate and canal geometry.

1. Introduction and background

Seventy percent of worldwide freshwater use is for irrigation (Hotchkisss et al., 2001). This figure is three times the amount used for industry and 10 times the amount used for domestic and urban use (Hotchkisss et al., 2001). According to an Interagency Task Force, the average off-farm water conveyance efficiency for irrigation in the United States is 78% (ITF, 1979) and conveyance loses account for 104 million $m^3 d^{-1}$ (Herschy and Fairbridge, 1998). This seepage represents 10 times the daily U.S. domestic water use (Herschy and Fairbridge, 1998). Analysis of earthen canal seepage in Pakistan and elsewhere has shown that a substantial amount of water is lost through low conveyance efficiency (Alam and Bhutta, 2004; Shahid et al., 1996; Strong and Barron, 1994; Lawler, 1990) and seepage losses from canals have been estimated to range between 15 and 45% of the total diverted volume (Van der Leen et al., 1990). Seepage losses from canals in the former U.S.S.R. have been quantified to represent 40–50% of the transported water (Kacimov, 1992). In India, the seepage loss has been estimated to account for 45% of the water diverted into canal systems (Sharma and Chawla, 1979). In the Lower Rio Grande Valley, canal seepage accounts for 30–36% of the total diverted water (Fipps, 2001). Although the seepage represents a significant portion of the total diverted water, a portion of the water is recovered through a drain system and can be reused within the Lower Rio Grande Valley.

The major factors that affect seepage rates in irrigation canals are soil permeability and types, canal length, length and shape of wetted perimeter, water depth, depth to the groundwater table, and presence of other constraints such as wells, drains, and impermeable soil layers (Akbar, 2005; Alam and Bhutta, 2004; Swamee et al., 2000; Swamee, 1994, 1995). Some less significant factors include sediment load and size distribution, age of the canal, presence of aquatic plants, viscosity, and salinity of the canal water (Akbar, 2005; Alam and Bhutta, 2004; Swamee et al., 2000).

Determining canal seepage is usually a quite difficult undertaking. Fluctuations in canal levels as well as groundwater levels can lead to variations throughout a year and within an irrigation season. Additionally, the amount lost to seepage often falls within the discharge measurement errors of traditional methods. Seepage has been traditionally determined using direct measurements, indirect methods, or by prediction (Bakry and Awad, 1997). Direct methods are based on measurements; indirect methods involve monitoring the water table adjacent to canals; and prediction involves applying developed equations or relationships. Common methods used to directly determine canal seepage include, ponding tests, infrared photography, bell-type seepage meters and electrical resistivity, and inflow and outflow measurements (Engelbert et al., 1997; Engelbert, 1993).

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Ponding tests may be the most accurate and dependable method of determining canal seepage loss in smaller canals (Bakry and Awad, 1997; Alam and Bhutta, 2004; Bodla et al., 1998) but are not suitable to all conditions. This method requires the diking of a canal and measuring the subsequent drop in water level over a period of time. Although this method can be accurate, it is intrusive and cannot be used conveniently on large irrigation canals or canals that convey water to other areas. Another drawback is that suspended material can settle out on the wetted perimeter and reduce the overall seepage rate (Alam and Bhutta, 2004). Additional drawbacks are removal or disruption of existing natural soil liner, high costs, and feasibility of performing tests at multiple locations.

Bell-type seepage meters use a seepage bell and a measuring cup to create a pressure differential that can be correlated with seepage rate. Overall, the reliability and ability to replicate bell-type seepage measurements is variable (Hotchkisss et al., 2001; Worstell and Carpenter, 1969), and subject to high user error, and it does not represent a viable method for determining canal seepage.

Infrared imagery can be used to determine areas of high seepage from vegetation cover as areas of high seepage have abundant vegetative growth in dry areas (Engelbert et al., 1997; Meyer, 1975). The main drawback of this method is that it does not actually quantify seepage and cannot be used in areas where sufficient groundwater exists for plant growth. Overall, this method can be useful in identifying areas where canal lining could be advantageous.

Electrical resistivity is another method that can be used to determine seepage rates. Areas of high seepage show increased electrical resistivity, but this method requires the development of a local quantitative relationship from actual measurements (Hotchkisss et al., 2001) which limits overall usefulness.

Inflow and outflow measurements require that direct measurements are taken at various transects along a canal. Traditionally the measurements are completed using propeller type or electromagnetic type flow meters, which are time consuming (Herschy, 1999; Rhoads et al., 2003) and do not allow for replicate measurements during an appropriate time frame. Additionally, the measurement error of this method often exceeds the amount of seepage measured (Alam and Bhutta, 2004). The inflow–outflow method also requires that the flow conditions remain steady in the measured reach (Alam and Bhutta, 2004). One advantage to the inflow–outflow method is that the seepage is measured under normal operating conditions and has been cited as the preferred method by several authors (Alam and Bhutta, 2004; Skogerboe et al., 1999; Dukker et al., 1994).

Overall, the inflow–outflow method has been the preferred method for determining seepage (Alam and Bhutta, 2004; Skogerboe et al., 1999; Dukker et al., 1994), but is limited by measurement accuracy, time required for measurement, and canal depth and discharge fluctuations. Through the use of an Acoustic Doppler Current Profiler (ADCP) the limitations of the inflow–outflow method can be addressed resulting in high quality, replicable, and efficient measurements of canal seepage.

ADCPs allow for rapid flow rate and velocity measurements in rivers and other open channels (Shields and Rigby, 2005), and have been in use before 1990 (Nystrom et al., 2007; Oberg et al., 2005; Oberg and Mueller, 1994). An ADCP measures the Doppler shift of acoustic signals that are reflected by suspended particles in the water (Rennie and Rainville, 2006; Shields and Rigby, 2005). In recent years the ADCP has become the standard for measuring river discharges as well as velocity distribution (Rennie and Rainville, 2006, 2008; Mueller et al., 2007; Oberg et al., 2005; Simpson, 2002; Oberg and Mueller, 1994). ADCP measurements have been shown to be more accurate and as reliable as traditional measurement techniques through various lab studies and comparison with known field measurement techniques (Muste et al., 2004a,b; Mueller, 2002; Nystrom et al., 2002; Shih et al., 2000; González et al., 1996; Morlock, 1996). Principles of ADCP function and operation are described in detail by Yorke and Oberg (2002), Gordon (1996) and Morlock (1996).

One of the primary advantages of an ADCP is the speed and detail in which data can be collected (Carr and Rehmann, 2007; Shields and Rigby, 2005; Huang, 2004). ADCPs provide for much higher spatial resolution and reduced disturbance of the flow (Carr and Rehmann, 2007). Additionally, the amount of data that can be collected about velocity characteristics for a given measurement location greatly exceeds traditional methods and techniques, such as propeller or electromagnetic meters (Carr and Rehmann, 2007; Shields and Rigby, 2005). ADCPs break the channel into thousands of velocity cells which provides data on flow patterns across a channel, allows for detailed velocity mapping, provides better spatial resolution, and is superior to the point velocity measurements of traditional meters (Carr and Rehmann, 2007; Mueller et al., 2007; Shields and Rigby, 2005). Similar to propeller or electromagnetic meters ADCP measurement techniques require limited calibration in the field (Nystrom et al., 2007). A significant benefit of the ADCP over traditional meters is that no intrusion into a water body is required, which decreases the risk to operators and increases the overall usefulness of the device (Nystrom et al., 2007).

ADCPs have wide ranging uses that also include discharge measurement, velocity measurements, turbulence measurements, sediment transport analyses, assessing aquatic habitat, validating numerical models and other geomorphic and hydraulic research (Carr and Rehmann, 2007; García et al., 2007; Nystrom et al., 2007; Mueller et al., 2007; Rennie et al., 2007; Dinehart and Burau, 2005; Shields and Rigby, 2005; Jacobson et al., 2004; Kostaschuk et al., 2004; Wagner and Mueller, 2001). Additionally ADCPs have been used successfully to establish index velocity rating curves in irrigation districts and have improved cost effectiveness, accuracy, and quality control of discharge measurements (Styles, 2005). To date ADCPs have not been extensively used for determining canal seepage although they have found widespread implementation for measuring stream flow. This paper presents the use of an ADCP in the Middle Rio Grande Valley to determine canal seepage rates.

2. Middle Rio Grande Conservancy District

The Middle Rio Grande Conservancy District (MRGCD; Fig. 1) was formed in 1925 in response to flooding and the deterioration of previously constructed irrigation works (Shah, 2001). The district stretches over a distance of approximately 193 km in the Middle Rio Grande Valley in Central New Mexico. Water diverted by the MRGCD originates as native flow of the Rio Grande and its tributaries, including the Rio Chama. The MRGCD services irrigators from Cochiti Reservoir to the northern boundary of the Bosque del Apache National Wildlife Refuge, with a total irrigated area of roughly 24,280 ha. Irrigation facilities managed by the MRGCD divert water from the river to service agricultural lands, which include small urban parcels and large tracts that produce alfalfa, pasture, corn, and vegetable crops such as the green chile which is famous throughout the southwest. The MRGCD supplies water to its four divisions – Cochiti, Albuquerque, Belen, and Socorro – through Cochiti Dam and Angostura, Isleta and San Acacia diversion weirs. Water is conveyed in the MRGCD by gravity flow through primarily earthen canals whose total length of canals exceeds 2400 km. During recent drought years, low natural flows combined with minimum stream flow requirements for the endangered Rio Grande Silvery Minnow have drastically reduced available water supplies.

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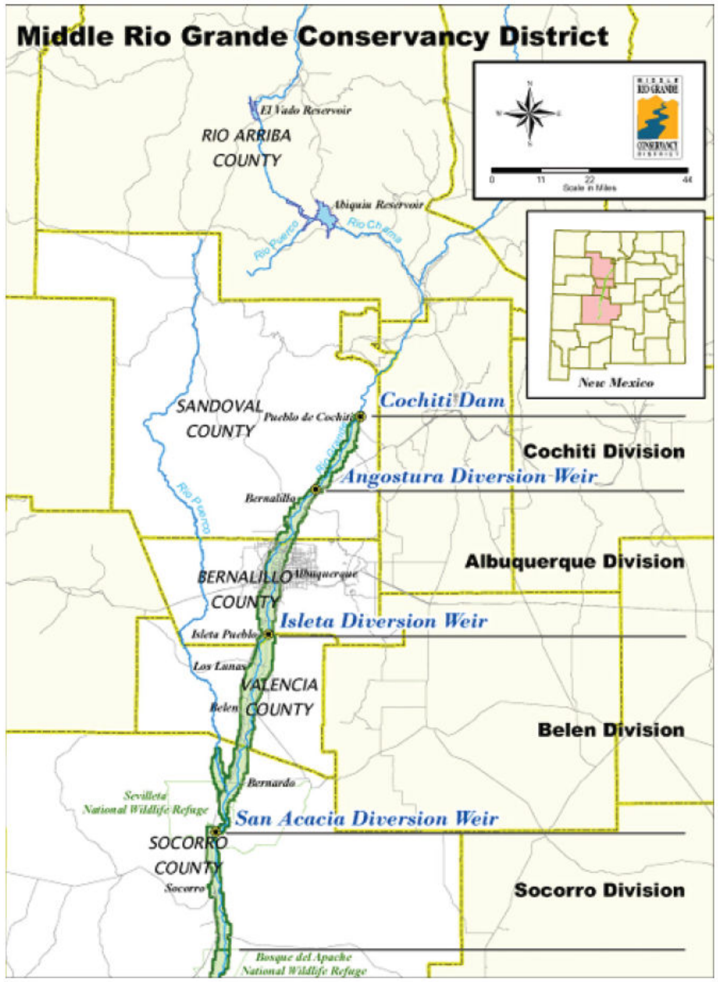

Fig. 1. The Middle Rio Grande Conservancy District.

In order to deal with reduced water availability, the MRGCD has taken a proactive approach to be a more efficient water user and service its irrigators with reduced river diversions. This will be accomplished through scheduled water delivery using a Decision Support System (DSS) (Oad et al., 2009) and an infrastructure modernization (Gensler et al., 2009) program.

Only limited measurements of canal seepage have been previously conducted in the Middle Rio Grande Valley and no equations have been developed to predict seepage loss. Since canal seepage losses can represent a significant portion of diverted water (Herschy and Fairbridge, 1998) and the MRGCD is focused on improving efficiency, a measurement study was conducted to determine canal seepage rates throughout the MRGCD. Additionally, the MRGCD has begun using the aforementioned DSS to schedule water deliveries and knowledge of canal seepage rates to determine DSS seepage loss parameters is essential for accurate canal operation. Through the availability of an ADCP this study provided the unique opportunity to apply advanced technology in determining irrigation canal seepage rates under normal operating conditions.

3. Materials and methods

The ADCP model used for this study was the Teledyne RD Instrument StreamPro. The StreamPro is designed to make moving boat discharge measurements in flow depths from 2.36 cm to 2 m (AuBuchon et al., 2008; Rehmel, 2006) and has a 2000-kHz frequency with a small four beam transducer head. The StreamPro is equipped with Bluetooth radio telemetry that allows for communication and data transmission between the ADCP and a Pocket PC–HP iPAQ. The Bluetooth range is approximately 60 m with a straight line of sight from the pocket PC to the transmitter mounted on the boat. This distance decreases significantly as battery power in the ADCP decreases (Teledyne RD Instruments, 2006a). Specific validation of the StreamPro shows that it compares favorable with discharges measured using other meters

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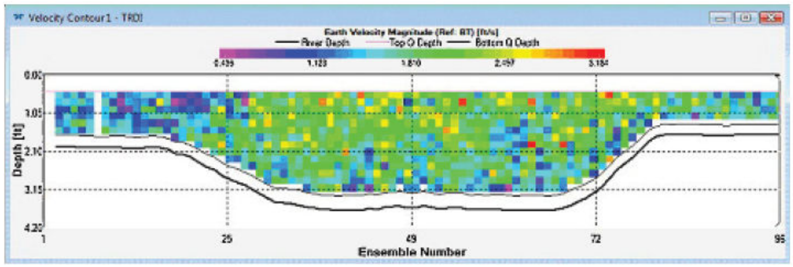

Fig. 2. Velocity profile measured by a StreamPro ADCP.

and there is no indication that StreamPro measurements are biased (Rehmel, 2006). The cost of the StreamPro ADCP is roughly 17,000 US$. This price includes the ADCP, floating trimaran, HP–iPAQ pocket PC, and processing and connecting software (AuBuchon et al., 2008). The processing software provides velocity profile data over an entire cross-section (Fig. 2).

The inflow–outflow method using an ADCP was chosen for the determination of canal seepage rates in the Middle Rio Grande Valley because it allows for measurement during normal operating conditions, is a non-intrusive measurement technique, and previous studies have established this as the preferred method in determining canal seepage (Alam and Bhutta, 2004; Skogerboe et al., 1999; Dukker et al., 1994). The inflow–outflow method is based on creating a water balance in an irrigation canal where inflow and outflow are measured a certain distance apart, also ensuring that no surface abstractions are occurring over the measurement reach. The use of an ADCP in tandem with pressure transducers ensured that measurement errors associated with fluctuations in water level were addressed. Coordination with water managers was essential to guarantee that inflow–outflow measured sections had no withdrawals through headgates occurring during the measurement period. Based on a previous study conducted by the MRGCD it was determined that open water evaporation from the canal system was negligible and therefore evaporation was not incorporated into the analysis of the water balance used to determine canal seepage.

4. Measurement protocol

The measurement protocol used for the collection of canal seepage data followed the standard USGS ADCP data collection method (Oberg et al., 2005; Rehmel, 2004; Simpson, 2001; Morlock, 1996). A bank-operated rope and pulley system was deployed and used to move the StreamPro across the channel and back for each transect measurement (Fig. 3). Bank-operated pulley set-ups allow for a more uniform pull, reduced boat motion, and consistent edge measurements. Rehmel (2006) found that consistently using a rope and pulley set-up reduces variability in measurement discharges.

Following installation of the pulley mechanism, Bluetooth communication was then enabled using the HP–iPAQ and test pings (echo of sonar pulses) were used to ensure that the unit was functioning properly. Next, the pinging mode on the StreamPro was used to establish maximum depth and velocity values for the measurement site by moving the boat across the transect using the pulley set-up. The values for maximum depth and maximum velocity were recorded and inputted into the iPAQ software. These values were used also by the StreamPro program to determine the bin size (also referred to as vertical depth cells), vertical sample area, and the size over which the ADCP measurements are averaged (AuBuchon et al., 2008). All data were collected using the ADCP water mode 12 (WM 12) that is a general purpose mode recommended by the manufacturer (RD Instruments) for high-resolution flow measurements in rivers, streams, and other bodies of water and is appropriate for measurements in small streams and irrigation canals.

Next, the StreamPro was brought to rest directly against the bank of the canal. In most cases, the number of ADCP depth cells recorded directly against each bank was zero due to shallow depth. Gradually the boat was moved away from the bank until the iPAQ showed that the StreamPro was measuring at least three good depth cells which exceeded the software requirement of at least two good depth cells. The boat position at that point was marked by affixing a clip to the pulley line so the position could be easily replicated. The distance from the canal edge to the boat position was then measured using a decimal tape with measurements recorded to the nearest 10th of a foot. This process was repeated for both banks of the irrigation canal and measurements for edge distance were inputted into the iPAQ software.

In order to verify that storage in the canal was not changing, pressure transducers and temporary staff gages were used during inflow and outflow measurements to monitor water level fluctuations. The pressure transducers used were HOBO brand data loggers manufactured by Onset Incorporated, data from which made it possible to determine the exact fluctuation in canal water level (Fig. 4).

Once the initial set-up and edge data collection were complete, four transects were collected using the USGS ADCP measurement guidelines (Oberg et al., 2005; Rehmel, 2004; Simpson, 2001; Morlock, 1996). The iPAQ software displayed the average of these four measurements and the standard deviation between the four measurements. If the standard deviation between the measurements exceeded 5% of the average, four more transects were

Fig. 3. Bank-operated rope and pulley system with operator and ADCP.

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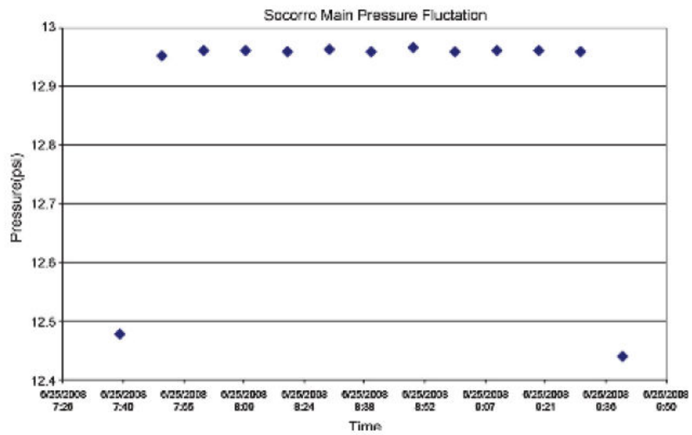

Fig. 4. Pressure fluctuations on Socorro Main measurement 6/25/2008.

collected following the standard USGS protocol. Measurements were conducted on three main canals, three lateral canals, and three acequia (tertiary) canals at three separate times during the irrigation season totalling 25 seepage measurements. The time span of the study was from June 11th to October 23rd 2008 with an early, middle, and late season measurement conducted for each canal to address seasonal variability. Table 1 displays the measurement matrix which consists of canal name, measurement date, and canal length over which seepage was measured.

The measurements consisted of measuring both an upstream inflow and a downstream outflow along a significant distance of canal. For each canal, a measurement site was established where a significant length of canal was available for inflow and outflow measurements without surface abstractions of the flow. To ensure that all irrigation had ceased on the canal, the measurement section was driven to validate that all headgates along the canal were indeed closed. This distance between upstream and downstream measurements was made as long as possible to ensure that a measurable amount of canal seepage could be detected, and in most cases exceeded 3.2 km (Table 1). GPS coordinates were taken at both the upstream and downstream measurement locations so that the exact distance between the two stations could be determined using Geographical Information System (GIS) software and maps were created for each canal section measured (Fig. 5).

Table 1
Measurement matrix displaying canal name, measurement data, and canal length over which seepage was measured.

Canal name	Measurement date	Length (km)
Belen Highline	6/13/2008	7.04
	8/12/2008	7.04
	10/7/2008	7.04
Socorro Main	6/25/2008	4.44
	8/13/2008	4.44
	10/15/2008	4.44
Albuquerque Main	7/3/2008	2.65
	10/23/2008	2.65
New Belen acequia	8/12/2008	3.36[a]
	10/7/2008	4.38
Bernalillo acequia	6/16/2008	5.87
	8/20/2008	5.87
	10/21/2008	5.87
Barr Main Canal	6/30/2008	6.72
	8/11/2008	6.72
	10/22/2008	6.72
Peralta acequia	6/26/2008	5.90
	8/27/2008	5.90
	10/15/2008	5.90
Sili Main	6/11/2008	5.73
	8/14/2008	5.73
	10/9/2008	5.73
Williams Lateral	6/30/2008	2.87
	8/11/2008	2.87
	10/17/2008	2.87

[a] Length was shorter because of open turnout downstream of original transect.

5. Data processing procedure

Quality assurance was completed for all transect and for each measurement location to minimize error. The first step was to analyze the fluctuation in water level collected from the pressure transducer. If the fluctuation in the water level exceeded 2.5% of the total flow depth, the entire measurement was discarded and repeated at a later date. The next step involved examining the individual transect summary in the WinRiver II data analysis software. For each individual transect the number of bins, % bad bins, number of ensembles, and number of bad ensembles were examined. If the number of bad ensembles or number of bad bins exceeded 10%, the transect was not used in computing the average discharge for a measurement.

Using the discharge summary in WinRiver II the boat speed versus water speed, total time of measurement, total number of ensembles, edge distances, discharge in unmeasured top and bottom zones of the transect, total flow area, and average flow velocity were compared for each transect. Any transect differing markedly from the other transects for any of the above metrics was not used in computing the average discharge for a measurement site. Additionally, the boat track feature was used to analyze each individual transect to insure that the boat progress was perpendicular across the irrigation canal. Once the analysis of all transects for a measurement site was complete, the average discharge from the WinRiver II discharge summary was taken as the flow rate for the measurement site.

The discharge summary for each measurement site included the data for total flow rate, top width, flow area, and depth. To determine the wetted perimeter of the measured cross-section,

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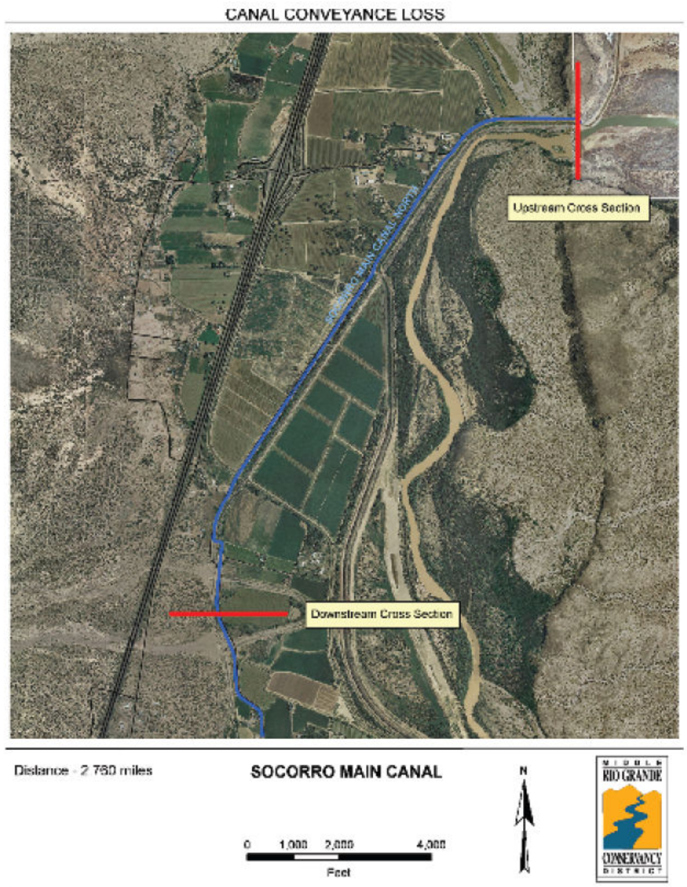

Fig. 5. Measurement cross-sections for Socorro Main canal conveyance loss.

raw data from the ADCP were exported from the ADCP WinRiver II software into Microsoft Excel using an ASCII file format. The ASCII files consisted of x (distance across canal) and y (canal depth) data components along the measured cross-section. The hypotenuse lengths for the right triangle in each ensemble represented the wetted perimeter for each ensemble. The sum of all hypotenuse components resulted in the total wetted perimeter of each canal section.

6. Results

The data collected and subsequent analysis resulted in a database that contained the following information for each seepage measurement location: maximum change in water level, percent change in flow depth, upstream flow rate, downstream flow rate, canal length over which seepage was measured, total change in flow rate across the measured distance, upstream wetted perimeter, upstream flow area, maximum depth upstream, upstream top width, upstream average flow velocity, and percent loss of the inflow rate per mile. The upstream data were chosen for the database so that predictive seepage equations could be applied to upstream channel characteristics. Upstream channel characteristics are well defined for automated measurement sites throughout the MRGCD, and upstream characteristics are also required for determining seepage in the DSS used for scheduled water delivery (Oad et al., 2009). Table 2 displays the database developed from the measurement matrix. Two measurements were removed because of water deliveries from the canal: the Albuquerque Main Canal on 8/20/2008 and on the New Belen acequia on 7/2/2008. This resulted in a total of 25 seepage measurements.

From the collected data it was determined that main canals exhibited the least amount of seepage with an average seepage rate of 0.64% per kilometer. Lateral canals and acequia canals exhibited a similar seepage rate with an average rate of 1.93% per kilometer and 1.84% per kilometer, respectively. It was also found that no statistically significant difference in seepage rates existed throughout the season for the nine study canals as the variation fell within the standard deviation. The seepage loss rates obtained resemble results obtained by Fipps (2001) for canal seepage in the Lower Rio Grande Valley. The results also correspond well with a study in a Utah irrigation district that found seepage rates of 2% per kilometer (Napan et al., 2009). The suspected reasons for lower seepage rates in main canals include sedimentation, groundwater and maintenance. The main canals in the MRGCD are all directly connected to the Rio Grande and receive significant fine sediment loads. As water is conveyed down the main canals the sediment eventually settles out in the main canals reducing sediment load in lateral and acequia canals. The settling out in main canals results in

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Table 2
Collected seepage data displaying canal name, measurement data, maximum change in water level, upstream and downstream flow rates, canal length over which seepage was measured, total change in flow rate, upstream wetted perimeter, upstream flow area, upstream maximum depth, upstream top width, upstream average flow velocity, and % loss per mile.

Canal	US flow rate (m^3/s)	DS flow rate (m^3/s)	Length (km)	Total change (m^3/s)	US wetted perimeter (m)	US flow area (m^2)	US max depth (m)	US top width (m)	US average flow velocity (m/s)	Percent loss per km
Main canals										
Belen Highline	6.29	6.22	7.04	0.08	16.86	106.09	1.01	15.74	0.70	0.17
Belen Highline	6.54	6.39	7.04	0.15	14.59	127.90	1.09	13.69	0.55	0.32
Belen Highline	4.50	4.21	7.04	0.29	13.80	105.43	1.06	12.28	0.46	0.91
Socorro Main	6.46	6.23	4.44	0.23	10.75	105.72	1.56	8.67	0.68	0.81
Socorro Main	4.57	4.43	4.44	0.14	9.20	78.64	1.08	8.27	0.63	0.67
Socorro Main	3.95	3.85	4.44	0.10	9.65	80.86	1.13	8.78	0.54	0.58
Albuquerque Main	3.98	3.91	2.65	0.07	9.20	72.73	1.35	7.99	0.60	0.70
Albuquerque Main	2.95	2.88	2.65	0.08	8.53	55.28	0.96	7.93	0.59	0.97
Lateral canals										
New Belen acequia	1.01	0.95	3.36	0.07	7.07	26.03	0.72	6.49	0.42	1.91
New Belen acequia	0.81	0.75	4.38	0.06	7.35	20.15	0.36	7.10	0.44	1.81
Bernalillo acequia	0.80	0.71	5.90	0.09	5.91	32.04	1.06	4.71	0.28	1.84
Bernalillo acequia	0.78	0.69	5.90	0.09	5.54	34.03	1.07	4.88	0.26	1.95
Bernalillo acequia	0.84	0.76	5.90	0.09	5.63	32.57	0.92	4.89	0.28	1.75
Barr Main Canal	1.46	1.22	6.72	0.24	6.20	33.39	0.71	5.51	0.46	2.43
Barr Main Canal	1.66	1.40	6.72	0.26	6.70	35.00	0.68	6.12	0.50	2.33
Barr Main Canal	1.43	1.29	6.72	0.14	6.56	34.13	0.66	5.89	0.44	1.44
Acequia or branch canals										
Peralta acequia	0.57	0.51	5.87	0.06	5.40	14.64	0.48	4.89	0.44	1.79
Peralta acequia	0.76	0.68	5.87	0.07	5.87	24.99	0.76	3.83	0.34	1.65
Peralta acequia	0.55	0.50	5.87	0.05	5.69	19.45	0.63	4.22	0.31	1.54
Sili Main	0.47	0.41	5.73	0.06	5.50	19.51	0.48	5.05	0.25	2.21
Sili Main	0.58	0.51	5.73	0.07	5.07	21.34	0.54	4.62	0.28	2.15
Sili Main	0.64	0.58	5.73	0.06	5.14	23.09	0.57	4.49	0.28	1.67
Williams Lateral	0.61	0.58	2.87	0.03	3.50	12.75	0.68	2.89	0.55	1.88
Williams Lateral	0.67	0.63	2.87	0.04	3.57	13.94	0.67	3.10	0.55	1.94
Williams Lateral	0.69	0.66	2.87	0.03	3.47	14.74	0.72	2.90	0.53	1.71

soil pores being clogged with finer silt and clay sediment, thereby reducing overall seepage. Another reason for reduced seepage in main canals is the close proximity to the river and subsequent groundwater. Since the main canals originate at the Rio Grande they are not elevated above the river and could be connected to groundwater. Such close proximity to the groundwater would result in a small or negligible gradient for seepage from canal bottoms and to groundwater. Finally, the main canals in the MRGCD receive the most attention when it comes to maintenance and dredging. The main canal shapes in the MRGCD most closely represent the optimized canal sections for minimized seepage presented by Swamee et al. (2000) and the continued maintenance of these main canals results in a more efficient canal shape and optimized water conveyance.

Further analysis of the data showed that trends in canal seepage rate existed for upstream flow rate, and the three canal geometry properties of upstream wetted perimeter, upstream flow area, and upstream top width. The data showed that as canal inflow rate decreased the seepage increased. For the wetted perimeter, flow area, and top width data, the seepage increased as these values decreased. In order to develop predictive equations, the characteristics of the upstream cross-section were related to the percent loss per mile.

6.1. Correlation between seepage loss and flow rate

Analyzing the data for seepage rate versus upstream flow rate exhibited an exponential trend (Fig. 6). This relationship exhibited a coefficient of determination (r^2) of 0.80 and is displayed in Fig. 6 as well as in Eq. (1).

$$S = 2.34\,e^{-0.28Q} \quad (1)$$

where S = percent seepage loss per kilometer (%) and Q = inflow discharge (m^3/s).

6.2. Correlation between seepage loss and canal geometry

In addition to analyzing the inflow rate versus seepage loss, geometric properties of the inflow canal were plotted against the seepage rate. The three geometric properties that exhibited the most significant predictive equations were wetted perimeter, flow area, and channel top width. The data for seepage rate versus upstream wetted perimeter exhibited an exponential trend (Fig. 7). The exponential relationship developed exhibited a coefficient of determination (r^2) of 0.79 and is displayed in Fig. 7 as well as in Eq. (2).

$$S = 4.54\,e^{0.17P} \quad (2)$$

where S = percent seepage loss per kilometer (%) and P = wetted perimeter (m).

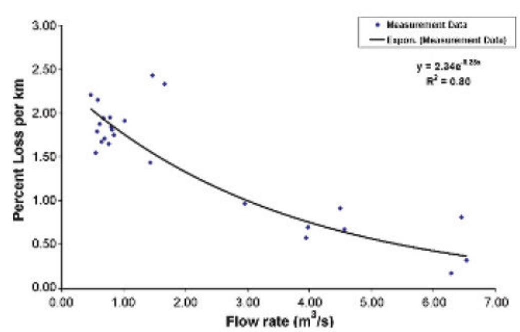

Fig. 6. Relationship between upstream flow rate and percent loss per mile.

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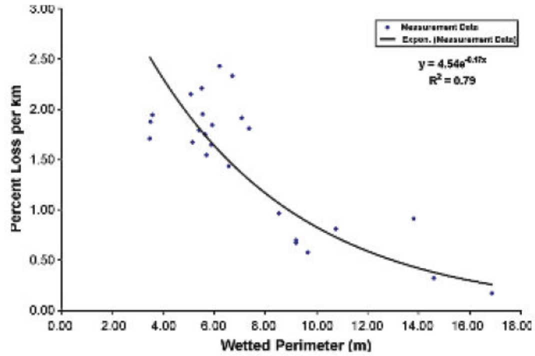

Fig. 7. Relationship between seepage loss and wetted perimeter.

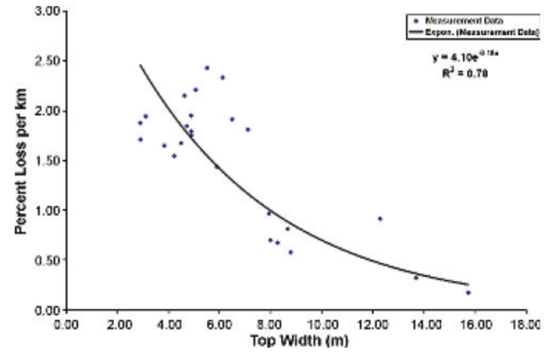

Fig. 9. Relationship between seepage loss and top width.

The data for seepage rate versus upstream flow area also exhibited an exponential trend (Fig. 8). The exponential relationship developed exhibited a coefficient of determination (r^2) of 0.76 and is displayed in Fig. 8 as well as Eq. (3).

$$S = 2.70\,e^{-0.18A} \tag{3}$$

where S = percent seepage loss per kilometer (%) and A = inflow area (m^2).

The data for seepage rate versus upstream top width also exhibited an exponential trend (Fig. 9). The exponential relationship developed exhibited a coefficient of determination (r^2) of 0.78 and is displayed in Fig. 9 as well as Eq. (4).

$$S = 4.10\,e^{-0.18T} \tag{4}$$

where S = percent seepage loss per kilometer (%) and T = top width (m).

Although the equation for top width is a function of velocity and cross-sectional area it will be useful to the MRGCD as ditch-riders and water managers will be able to predict seepage using only the top width of a canal.

Overall, the four developed equations display similar exponential trends. The variation in the collected data is minimal and the four equations are significant as the coefficient of determination (r^2) is not <0.76 for any of the developed equations. These equations present the opportunity to predict canal seepage losses based on the four easily measured parameters of inflow rate, wetted perimeter, flow area, and top width. These equations should only be applied to similar systems and to canals that are comparable in size to the ones measured during this study (inflow rate of 0.47–6.54 m^3/s for Eq. (1); wetted perimeter of 3.47–16.86 m for Eq. (2); flow area of 12.75–127.9 m^2 for Eq. (3); and top width of 2.89–15.74 m for Eq. (4)). The developed equations display r^2 values similar to other published studies. A study by Hotchkisss et al. (2001) in Nebraska was able to develop predictive canal seepage equations with coefficients of determination of 0.64 and 0.77. Another study in Australia by Akbar (2005) developed numerous predictive seepage equations with coefficients of determination ranging between 0.40 and 0.93. The developed equations also compare well with equations developed for irrigation canals in Egypt also using the inflow–outflow measurement methodology. Bakry and Awad (1997) were able to develop several predictive equations that relate inflow discharge, flow depth, and wetted perimeter to the seepage loss along irrigation canals (Bakry and Awad, 1997). The equations all exhibited a coefficient of determination (r^2) around 0.80 and have been successfully used to predict irrigation canal seepage below the Aswan High Dam (Bakry and Awad, 1997). Through the development of the equations for the MRGCD, district managers are able to predict seepage in a similar manner. Using the developed seepage equations the total seepage in the MRGCD for 2008 was calculated to be 72,000 acre-feet which is 20% of the total diversion. A similar seepage rate of 15% of the total diversion was found in an Alberta irrigation district (Iqbal et al., 2002).

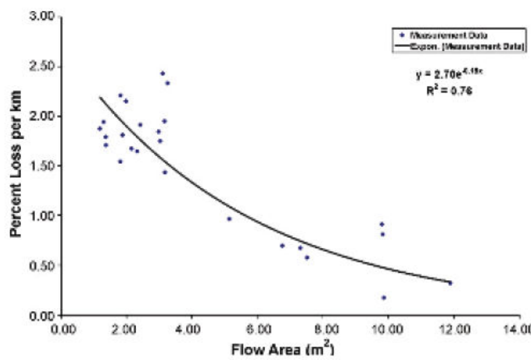

Fig. 8. Relationship between seepage loss and flow area.

7. Discussion and conclusion

The completed study to examine canal seepage in the MRGCD provides the framework for using advantaged technology in the form of an ADCP to determine canal seepage in an irrigation district. ADCPs offer the benefit of reducing measurement error, measurement time, offer high-resolution data collection, are non-intrusive, and allow for the collection of canal seepage data during normal canal operation. Coupled with a pressure transducer to ensure that canal fluctuations are limited, the presented methodology using an ADCP offers the opportunity to determine canal seepage quickly, accurately, and efficiently.

The measurement effort resulted in 25 independent measurements of canal seepage throughout the MRGCD. These measurements were conducted on main, lateral and acequia canals to ensure that various canal sizes were accounted for. Based on other studies (Fipps, 2001; Hotchkisss et al., 2001; Bakry and Awad, 1997) the results obtained for canal seepage are reasonable. From the collected data four predicative equations for canal seepage

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were developed.

$$S = 2.34\,e^{-0.28Q} \quad (1)$$

$$S = 4.54\,e^{-0.17P} \quad (2)$$

$$S = 2.70\,e^{-0.18A} \quad (3)$$

$$S = 4.10\,e^{-0.18T} \quad (4)$$

where S = percent seepage loss per kilometer (%); Q = inflow discharge (m^3/s); P = wetted perimeter (m); A = inflow area (m^2); T = top width (m).

The developed equations only apply to the Middle Rio Grande Valley or to irrigation systems that are geologically and hydrologically similar. Although the data collected to develop the equations showed no significant seasonal variation there is the possibility that seepage varies from year to year and further investigation is necessary. The two most useful equations to the MRGCD will most likely be Eqs. (1) and (4) which relate canal inflow and top width to seepage loss rate, respectively. The variables of canal inflow and canal top width are easily obtainable and require minimal effort for data collection. The MRGCD utilizes a network of automated measurement stations (Gensler et al., 2009) which will aid in determining canal inflow, which can then directly be related to a canal seepage rate. Determining the canal top width will also be quite straightforward as many bridges exist across canals allowing ditch-riders and water masters to measure the canal top width to obtain an estimate for canal seepage.

Using diversion records obtained from the automated measurement network, the MRGCD will also be able to quantify the aquifer recharge from the canal system in the Middle Rio Grande Valley. The length of each canal as well as the inflow for said canal is well defined and the developed equations will allow for calculation of canal seepage rate. The benefit to the MRGCD will be proving the amount of water that the canal system recharges to the regional aquifer. The city of Albuquerque and several smaller communities pump from the regional aquifer, and it is believed that aquifer levels are maintained through the seepage from the Rio Grande and MRGCD irrigation canals. Quantifying the amount of seepage that occurs from the MRGCD canals will prove the benefit that the canal network has on the local aquifer and aid the MRGCD in water rights litigation. Application of the developed equations will also have the benefit of determining areas where canal maintenance or lining would have the greatest benefit in water saving.

The predictive equations have also been used in the MRGCD DSS. The MRGCD DSS is used in scheduling demand based water deliveries throughout the irrigation system and knowledge of the canal seepage is crucial in determining the optimal water delivery required (Oad et al., 2009). Through the development of the equations from the seepage study, the accuracy of the DSS has been greatly improved. Overall, the use of ADCP technology to determine canal seepage offers an improvement over traditional methods. ADCPs provide a high-resolution, accurate, reliable and both time and cost effective measurement technique. It is the hope of the authors that ADCP technology finds acceptance and becomes a more widespread tool for determining seepage losses in canal systems.

Acknowledgements

The authors would like to thank the New Mexico Interstate Stream Commission and the Endangered Species Act Collaborative Program in New Mexico for their financial support and overall leadership. The National Science Foundation provided support in the form of graduate student scholarships which is also greatly appreciated. The staff of the MRGCD has provided invaluable logistical support and guidance to the project, which is greatly appreciated.

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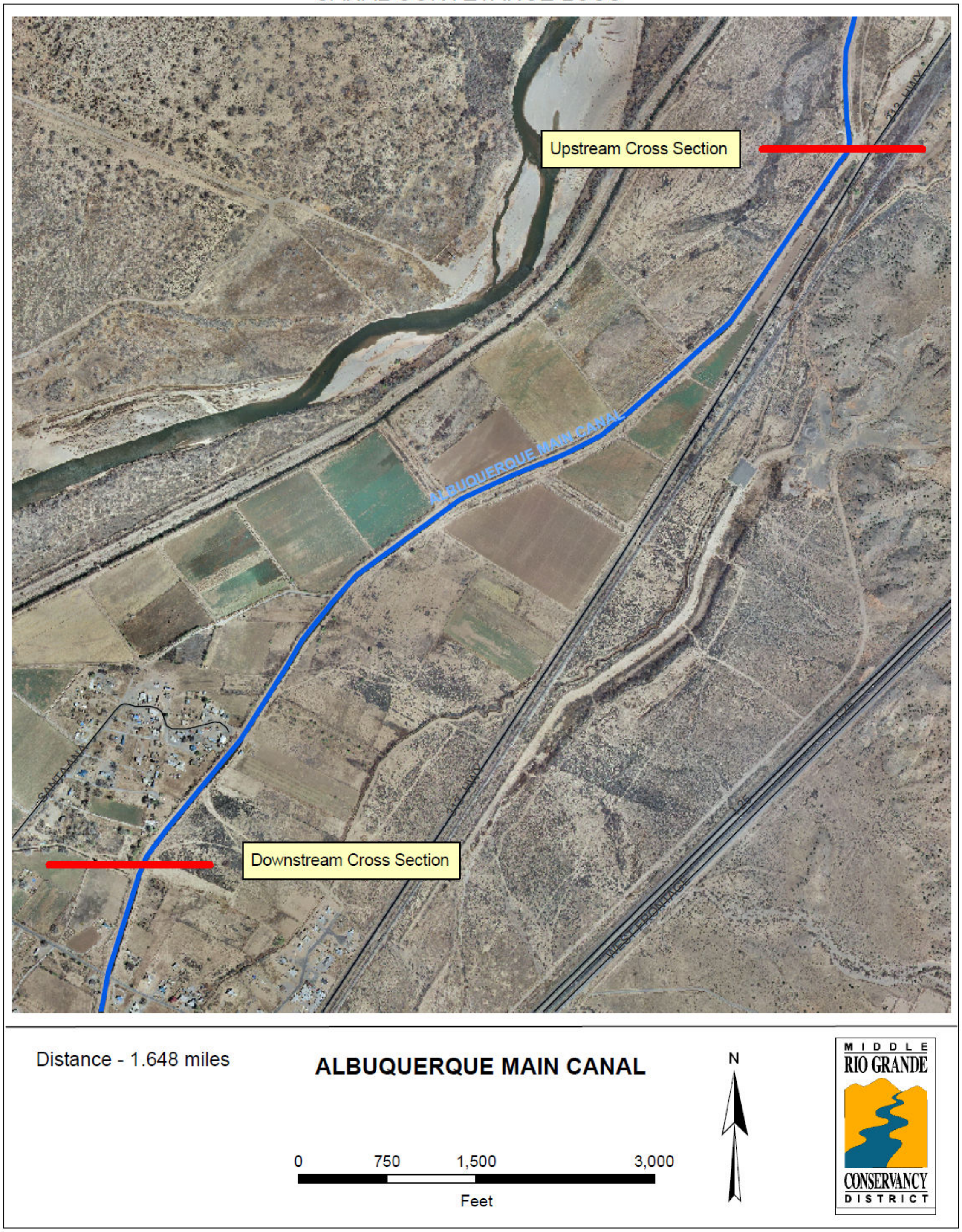
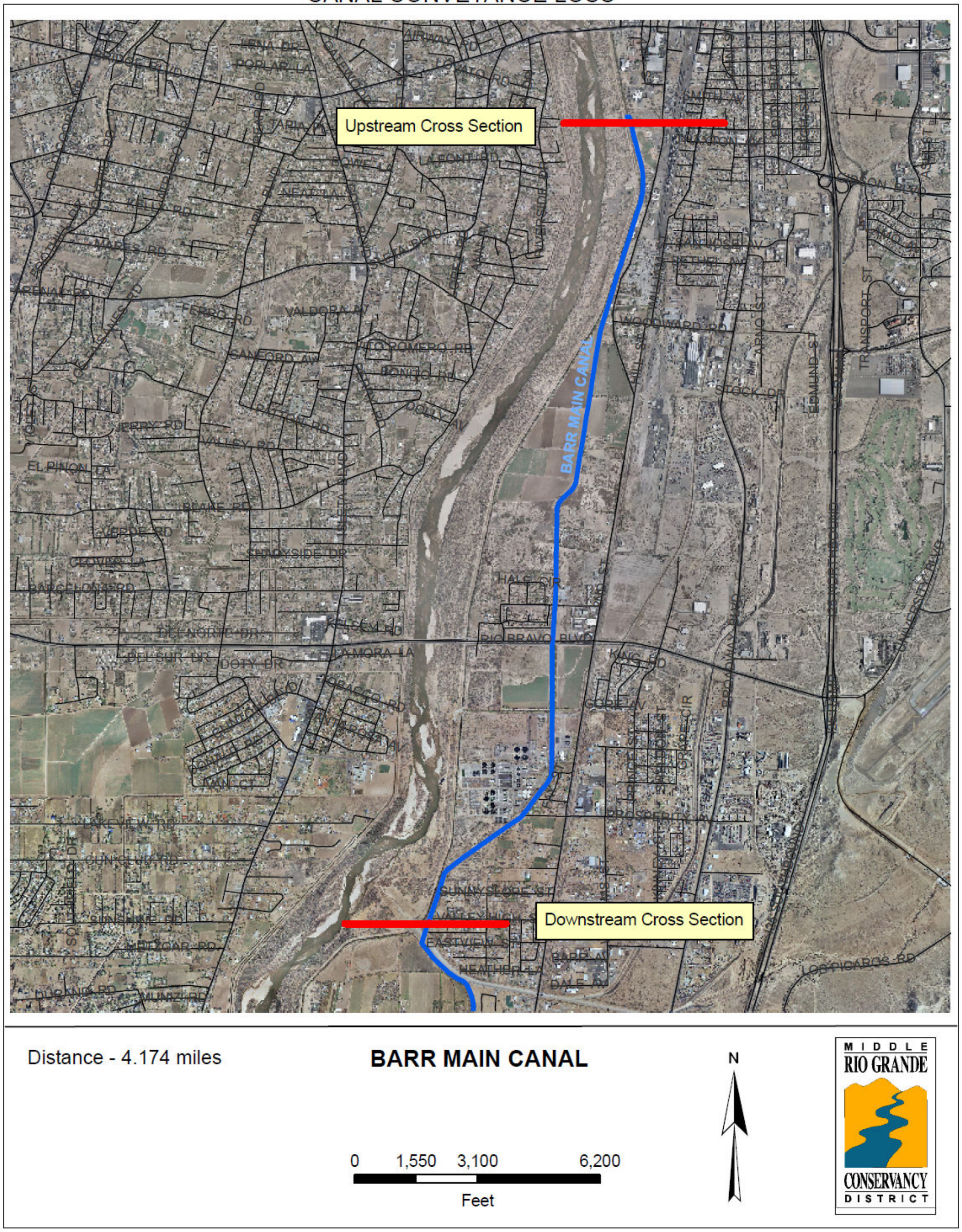
APPENDIX N: MAPS OF CANALS MEASURED DURING SEEPAGE STUDY

CANAL CONVEYANCE LOSS



CANAL CONVEYANCE LOSS



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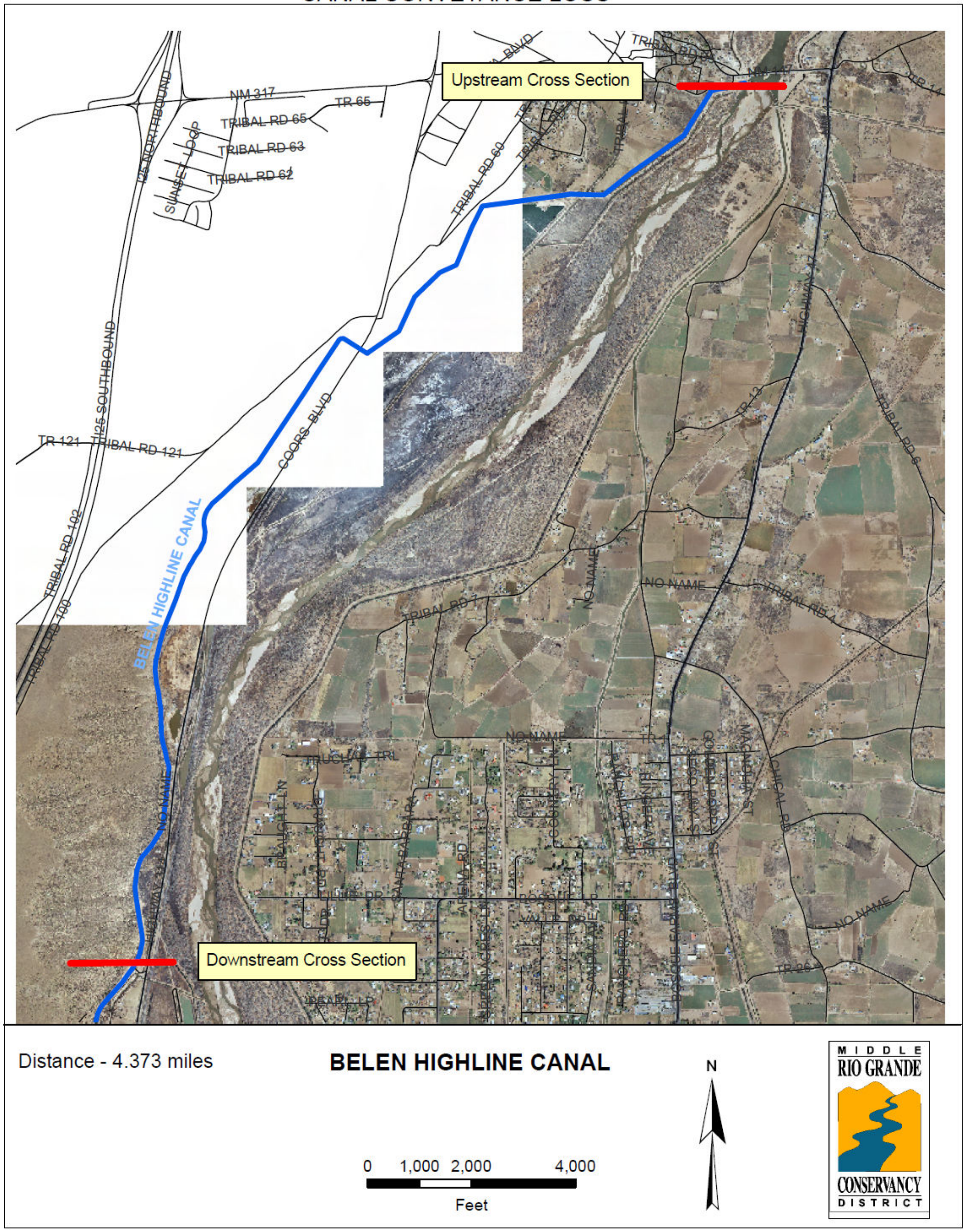

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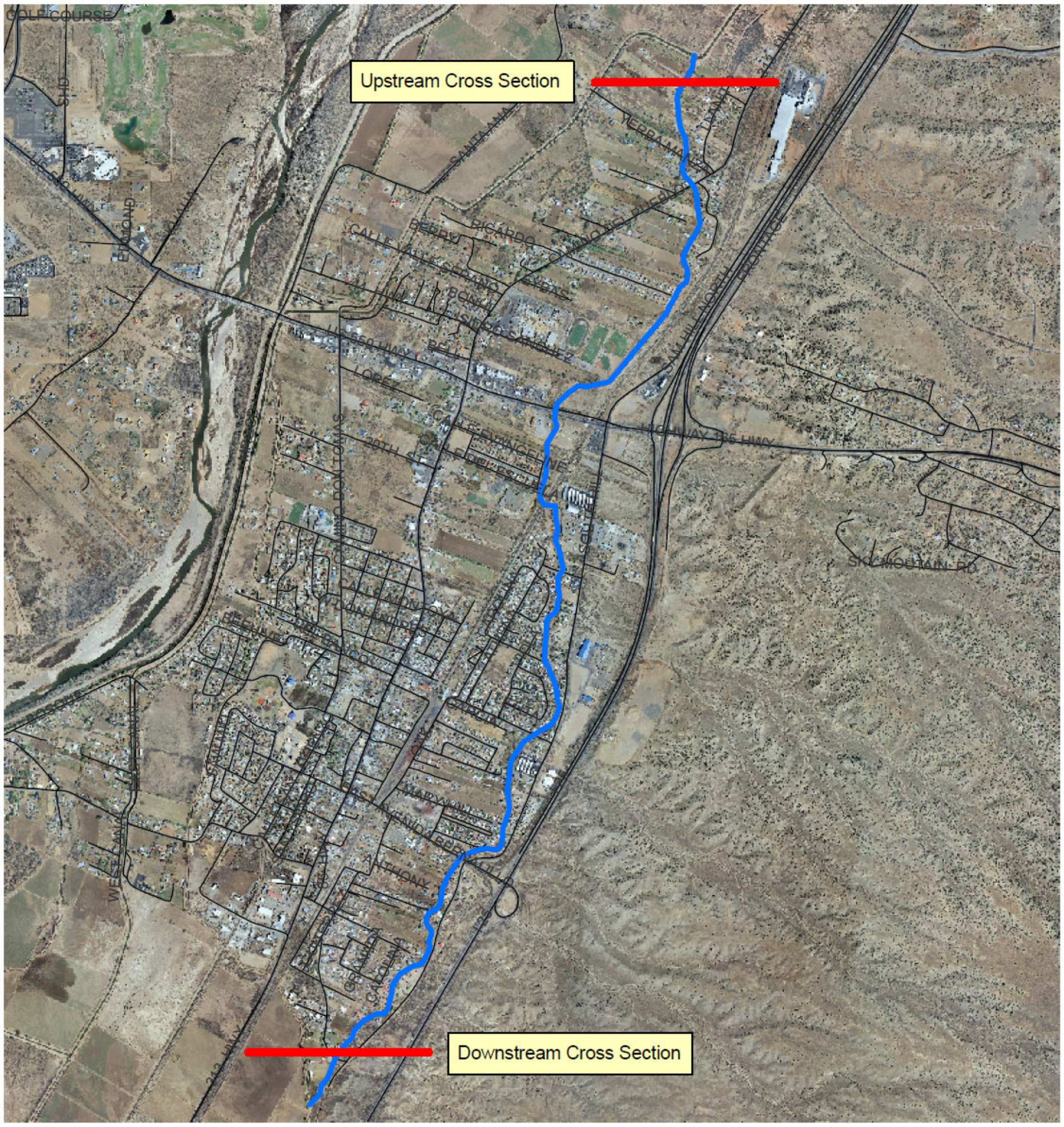


Distance - 3.665 miles

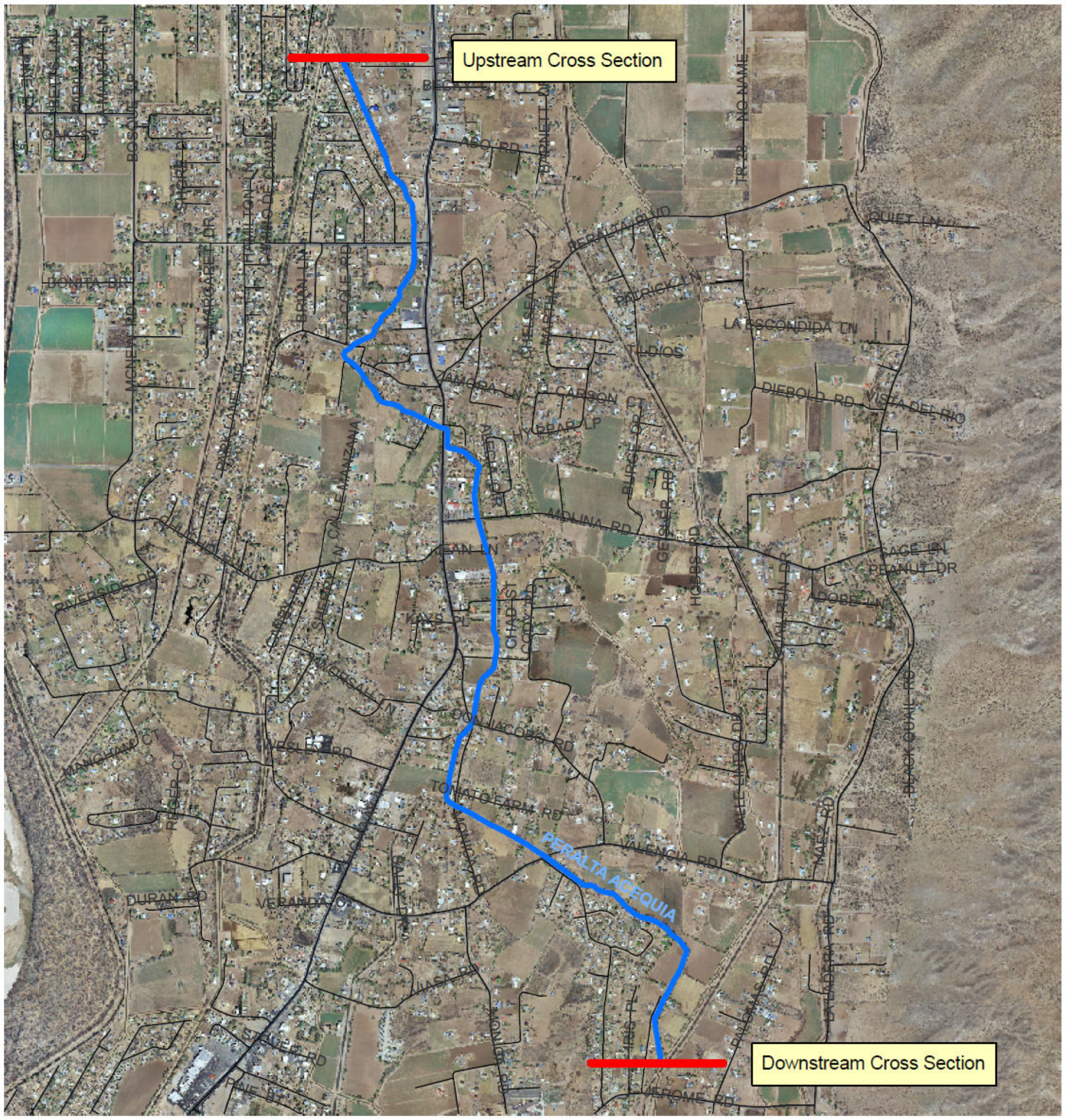
BERNALILLO ACEQUIA

0 1,200 2,400 4,800
Feet

N

CANAL CONVEYANCE LOSS

CANAL CONVEYANCE LOSS



Distance - 3.648 miles

PERALTA ACEQUIA

0 1,000 2,000 4,000
Feet

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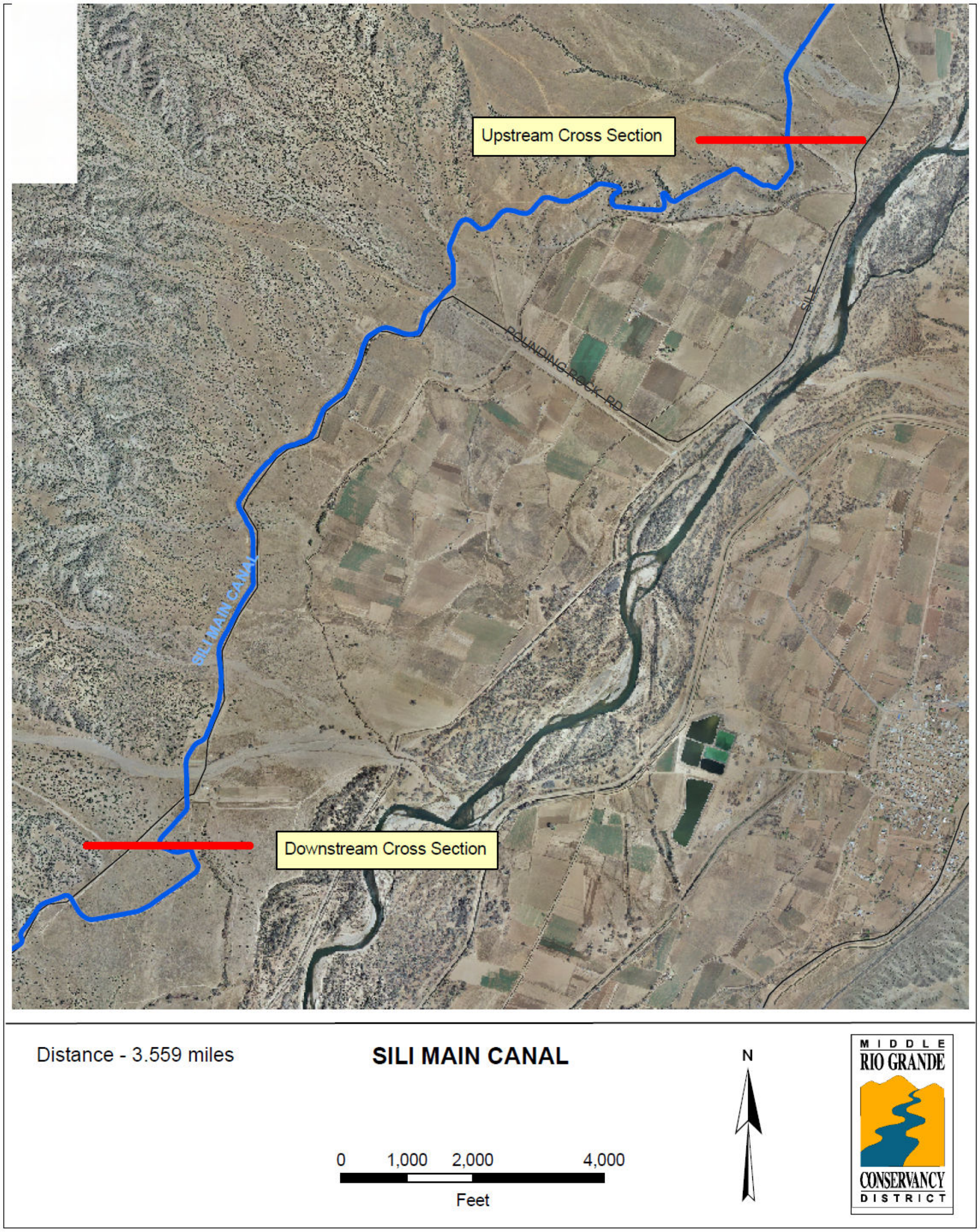
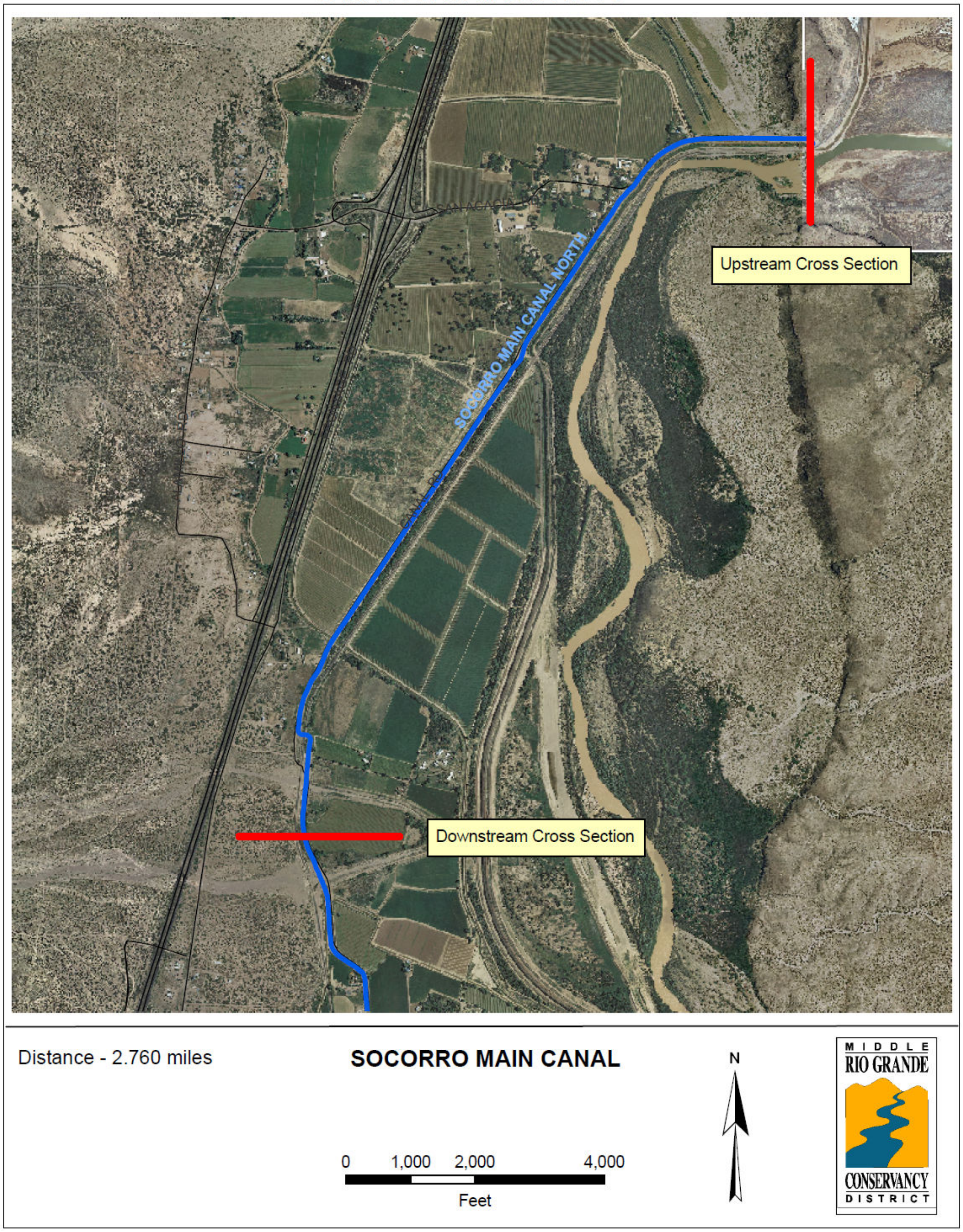
MIDDLE RIO GRANDE CONSERVANCY DISTRICT

CANAL CONVEYANCE LOSS



CANAL CONVEYANCE LOSS



CANAL CONVEYANCE LOSS

APPENDIX O: GENSLER, OAD, AND KINZLI (2009)

IRRIGATION SYSTEM MODERNIZATION: CASE STUDY OF THE MIDDLE RIO GRANDE

Irrigation System Modernization: Case Study of the Middle Rio Grande Valley

David Gensler[1]; Ramchand Oad[2]; and Kristoph-Dietrich Kinzli[3]

Abstract: The Middle Rio Grande Conservancy District (MRGCD) was officially founded in the 1920s, but it may well be the oldest operating irrigation system in North America. Currently the MRGCD serves about 22,300 ha of irrigated land and provides additional benefits to the Middle Rio Grande MRG Valley by providing proper soil drainage and protection against flooding. In recent years, the demand for water in the MRG Valley has increased drastically due to explosive population growth, expanding industry, and water allocated for environmental and ecological concerns, which include two federally listed endangered species—the silvery minnow (*Hybognathus amarus*) and the southwestern willow fly catcher (*Empidonax traillii extimus*). In response to the call for more efficient water use, the MRGCD embarked on a program of irrigation system modernization with supervisory control and data acquisition (SCADA) incorporation. Over the past few years, the MRGCD has developed a SCADA system focused on improving water use efficiency throughout the MRG Valley. This paper examines the five components of the system and how each component was developed and incorporated in the overall SCADA system. The SCADA system and related improvements in operational practices have reduced MRGCD river diversions from 7.4×10^8 m^3/year a decade ago to an average of 4.3172×10^8 m^3/year over the last 3 years.

DOI: 10.1061/(ASCE)0733-9437(2009)135:2(169)

CE Database subject headings: Automation; Irrigation systems; Decision support systems; Droughts; Control structures; Surface water.

Introduction

Middle Rio Grande Valley

The Middle Rio Grande (MRG) Valley extends 322 km, north to south, through central New Mexico from the Cochiti Reservoir to the headwaters of Elephant Butte Reservoir (Oad and Kullman 2006). The Rio Grande passes through this valley on its journey from the high country of Colorado and northern New Mexico, to the Gulf of Mexico. Throughout the MRG Valley, the Rio Grande is bordered by bosque, or riverside forest. Adjacent to the bosque, but within the narrow historic floodplain of the river, there is widespread irrigated agriculture. The City of Albuquerque and several smaller communities are located in and adjacent to the MRG Valley. Although the valley receives less than 25 cm of rainfall annually, the MRG supports both productive agriculture, and a rich and diverse ecosystem of fish and wildlife (Oad et al. 2008).

Water supply available for use in the MRG Valley includes: native flow of the Rio Grande and its tributaries, allocated according to the Rio Grande Compact of 1938; the San Juan-Chama project water, obtained via a trans-mountain diversion from the Colorado River system; and groundwater (Rio Grande Compact 1938). Water is fully appropriated in the MRG Valley, and its utilization is limited by the Rio Grande Compact. The compact sets forth a schedule of deliveries of native Rio Grande water from Colorado to New Mexico and from New Mexico to Texas (Rio Grande Compact 1938). A detailed analysis of water consumption throughout the valley has been completed by the New Mexico Interstate Stream Commission and can be found at http://www.ose.state.nm.us/water-info/mrgwss/index.html.

In addition to agricultural and domestic consumers, there is major water use in the MRG associated with riparian vegetation. Open water evaporation from reservoirs and the river is also substantial. Across the American West, irrigated agriculture uses roughly 80 to 90% of available surface water (Oad et al. 2008; Oad and Kullman, 2006). In the MRG use is more or less equally divided between agriculture, domestic use, and riparian consumption. Superimposed on these demands are river flow targets associated with two federally-listed endangered species: the silvery minnow (*Hybognathus amarus*) and the southwestern willow fly catcher (*Empidonax traillii extimus*) (USFWS 2003).

Middle Rio Grande Conservancy District

The Middle Rio Grande Conservancy District (MRGCD) may well be the oldest operating irrigation system in North America. Irrigation practices introduced by Spanish explorers in the 1600s supplanted prehistoric flood irrigation by the area's Pueblo Indians. At the time of Albuquerque's founding in 1706, the ditches which now constitute the MRGCD were in existence, operating as independent acequia associations. Acequias consisted of farmer groups that maintained individual irrigation canals. The acequia system was introduced to the MRG Valley by Spanish settlers. In acequia communities each farmer was responsible for maintaining

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a certain length of canal and would in return receive irrigation water. The use of irrigation water was managed by an elected mayordomo (ditch rider). Irrigated agriculture in the MRG Valley reached its greatest extent in the 1880s, but thereafter underwent a significant decline.

Surprisingly, this decline was caused by an overabundance of water. By the early 1920s inadequate drainage, periodic flooding, and climatic variables had resulted in water logged soils throughout the MRG Valley. Swamps, seeps, and salinization of agricultural lands were the result. In 1925, the State of New Mexico passed the Conservancy Act, which authorized creation of the MRGCD, which was accomplished by combining 79 independent acequia associations into a single entity. Fig. 1 displays a map of the MRGCD. Irrigated lands of six Indian Pueblos were also incorporated within the service area of the MRGCD. Physical construction began in 1928, and was completed by 1932 with river headings of acequias becoming laterals, consolidated by building six diversion works and a series of main canals. A high mountain storage reservoir, El Vado, was completed in 1935.

In the mid-1990s the MRGCD encountered the same pressures for change currently being experienced by irrigated agriculture throughout the world. An ever-expanding urban population began looking toward agriculture as a source for water and the Endangered Species Act of 1973, which is federal legislation, placed constraints on water use. Information on climate variability and groundwater resources produced a realization that water resources were less plentiful in the region than was previously believed. In order to proactively address water shortages and agricultural water delivery, the MRGCD embarked on a comprehensive program of canal modernization and supervisory control and data acquisition (SCADA) incorporation.

MRGCD SCADA Development and Use

The MRGCD program of measurement and automation was built entirely in-house using inexpensive components due to budget constraints. The components used in the system are a combination of traditional agricultural SCADA technology and adaptations of technology from other sectors of industry, most notably, the steel manufacturing industry. This combination and integration of technology makes the MRGCD SCADA setup unique. The MRGCD SCADA system can be broken into the following components:

- Flow measurement structures;
- Automated control structures;
- Instrumentation;
- Telemetry; and
- Software.

Water Measurement

Water measurement is the single most important component of the MRGCD's SCADA experience, as all operational decisions require sound knowledge of available water supplies and the demand throughout the system. When the MRGCD was initially constructed, considerable thought to water measurement was given. Starting in the early 1950s, gauging stations equipped with measurement instrumentation gradually deteriorated and quality of flow records declined.

In 1996, crisis struck the MRGCD in the form of drought, endangered species flow requirements, and development of municipal water supplies. At the time, the MRGCD was operating only 15 gauges on 1,930 km of canals. The following year, MRGCD officially embarked upon its modernization program. The construction of new flow gauges was the first step in this program. New gauges were constructed at key points in the canal system, notably at water diversion structures and at return flow points. The acquisition of data from these locations led to determining where additional gauges would be most useful.

Fig. 2. Broad crested weir gauging station with radio telemetry

Along with the increase in the number of gauging stations, efforts were made to improve the quality of measurement. Open-channel gauging sites with no control structures gave way to site-specific measuring structures. In the past, a variety of flow measurement structures was built in the MRGCD and includes sharp crested weirs, broad crested weirs, adjustable weirs, and Parshall flumes. Soon after beginning the modernization program, the Bureau of Reclamation WINFLUME software became available. Since that time, new gauges have been constructed with broad-crested weirs using WINFLUME for design and calibration. Fig. 2 displays a broad crested weir with radio telemetry. Currently, the MRGCD is operating 75 gauges.

Automated Control Structures

With the advent of better data collection, it became apparent that automated control was necessary. Data from gauges revealed that many operational problems occurred because canal operators could not be physically present at all times. Automation followed shortly thereafter with an experimental effort at a wasteway that had been fitted with an automated Langemann gate for water measurement, and was therefore a practical starting point. The MRGCD built the electronic controller and created the control software for this first automated gate, borrowing heavily from Bureau of Reclamation experience in Utah. Success with the first automated structure led to installation of over 40 additional automated structures. After the first in-house development of automation, it was found practical to use existing commercial control products, although the experience gained from initial development proved invaluable.

Most of MRGCD's recent automation efforts have involved the installation of Langemann overshot gates (Aqua Systems 2006). The majority of these can be easily retrofitted to existing structures, though some involve the construction of new check or heading structures. The Langemann gate has the capability to maintain a constant upstream water level as a check structure or it can provide a constant flow rate to downstream users. Fig. 3 displays a Langemann gate used as a canal heading. The Langemann gate is equipped with solar panels to power both gate operation and telemetry units. The gates employ integrated

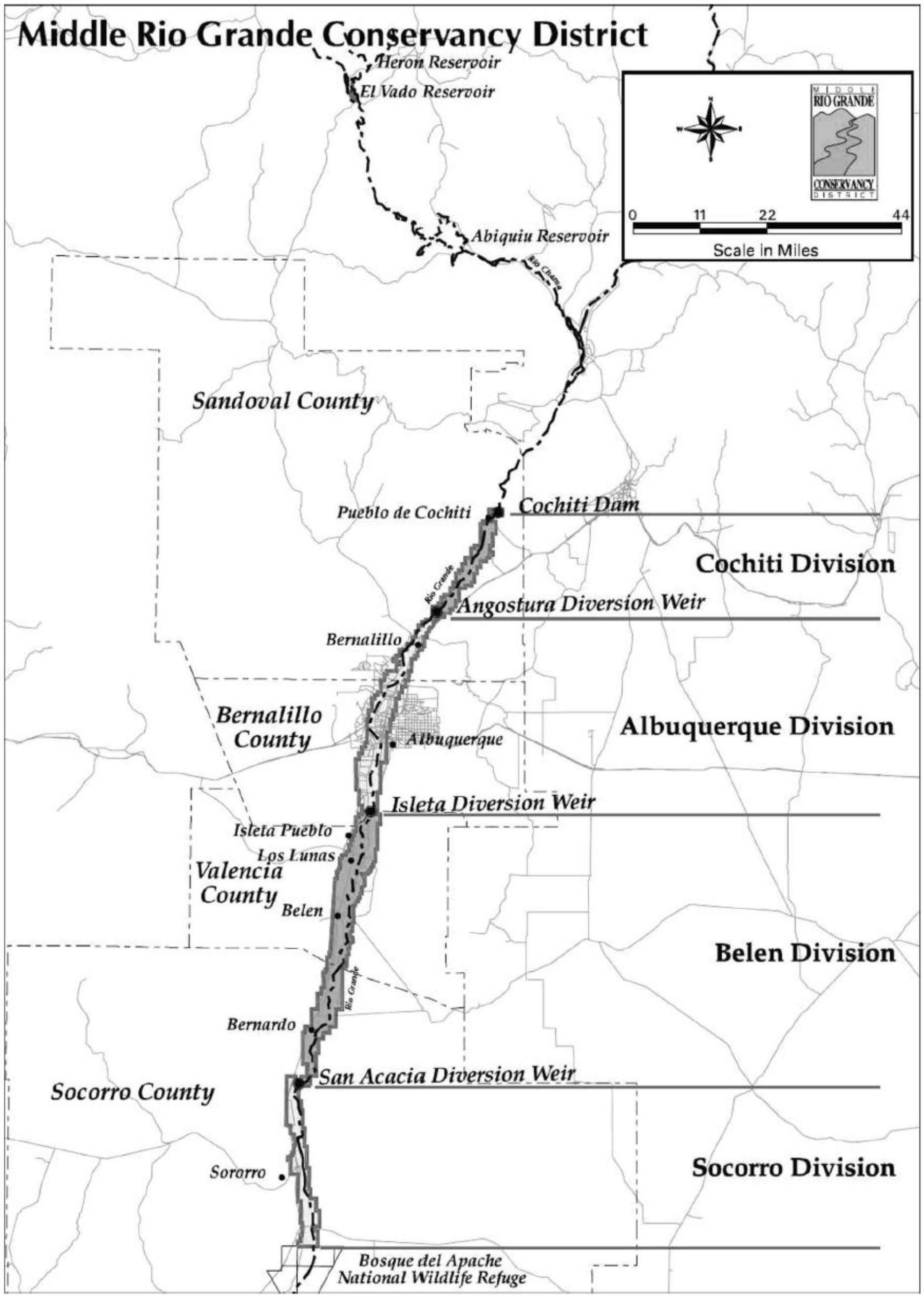

Fig. 1. Middle Rio Grande Conservancy District

Fig. 3. Langemann gate used as a canal heading

electronic controllers built around Control Design Incorporated (CDI) radio terminal units (RTUs) and Aqua Systems 2000 software. Langemann gates in the MRGCD are used as checks, turnouts, spillways, and diversion structures.

Some existing radial gates have also been automated. Conversion involves selection of a gearbox, motor, and controller. Some fabrication is involved to adapt the drive unit to the existing gate hoist shaft, but this is all done in-house by MRGCD shop personnel. Early conversion attempts used an AMI controller (Z-world, Sacremento, CA) supplied by Aqua Systems 2000, but recently the MRGCD has used the CDI RTU, which can be programmed to calculate flow through automated radial gates. Fig. 4 displays a CDI RTU. Though not as accurate as overshot gates, this is useful for setting target bypass flows at diversion structures for endangered species flow requirements.

Instrumentation

Flow measurement and automated control must include some level of instrumentation. In the 1930s, a float in a stilling well driving a pen across a revolving strip of paper was adequate. In fact, at the beginning of modernization efforts, the MRGCD was still using 15 Stevens A-71 stage recorders (Stevens Water, Portlans, OR). Diversions into the canal system were only known after the strip charts were collected and reduced at the end of the irrigation season.

Modernization meant a device was needed to generate an electrical or electronic output that could be digitally stored or transmitted. Initially, shaft encoders were used for this purpose, providing input for electronic data loggers. Experimentation with submersible pressure sensors soon followed, and these have been adopted, although a number of shaft encoders are still in use. Recently, sonar sensors have been used satisfactorily at a number of sites. The MRGCD has learned that different situations call for specific sensor types and sensors are selected for applications where they are most appropriate.

Telemetry

Data from electronic data loggers were initially downloaded manually and proved to be only a minimal improvement over strip chart recording, though processing was much faster. To address data downloading concerns telemetry was adopted to bring the recorded data back to MRGCD headquarters at regular intervals. Fig. 2 displays the telemetry associated with a broad crested weir. The MRGCD's initial exposure to telemetry was through the addition of Geostationary Orbiting Earth Satellite (GOES) satellite transmitters to existing electronic data loggers. This method worked, but had limitations. Data could only be transmitted periodically, and at regularly scheduled intervals. Of greater consequence was that the GOES system, at least as used by MRGCD, was a one-way link. Data could be received from gauging stations, but not sent back to them. As experiments with automation progressed, it was clear that reliable two-way communication would be a necessity.

To address the rising cost of phone service, experiments with FM radio telemetry were conducted. These began as a way to bring multiple stream gauge sites to a central data logger, which would then be relayed via GOES to MRGCD. First attempts with FM radio were not encouraging; however, a successful system was eventually developed. As the use of FM radio telemetry (licensed 450 mHz) expanded, and knowledge of radio telemetry grew, it was soon realized that data could be directly transmitted to MRGCD headquarters without using the GOES system.

The shift to FM radio produced what is one of the more unique features of the MRGCD telemetry system. The data link proved so reliable, that there was no longer a need to store data on site, and the use of data loggers was mostly discontinued, the exception being weather stations. In effect, a single desktop computer at the MRGCD headquarters has become the data logger for the entire stream gauge and gate system, being connected to sensors in the field through the FM radio link. Three repeater sites are used to relay data up and down the length of the valley, with transmission being up to 75 mi. Also, this has the benefit of being a two-way link, so various setup and control parameters can be transmitted to devices along the canals.

The MRGCD telemetry network consists exclusively of CDI RTUs. Fig. 4 displays a CDI RTU. Several different types of these units are used, depending on the application. The simplest units contain only a modem and radio, and transmit collected and processed weather station data from Campbell Scientific CR10X data loggers.

The majority of the RTUs contain a modem, radio, and an input/output (I/O) board packaged into a single unit. This combination of components allows for cheaper instrumentation with each site costing roughly $2,500, versus $10,000 for the separate components. Sensors can be connected directly to these and read remotely over the radio link. A variety of analog (4–20 mA, 0–20 mA, 0–5 V) and digital (SDI-12, RS-485) output devices can be accommodated this way. Another type includes a programmable (RP-52 BASIC) controller in the modem/radio/(I/O) unit. This style is used for all automatic control sites and places where unusual processing of sensor outputs such as averaging values, combining values, or timed functions, are required. At the present time, the MRGCD telemetry network gathers data from 75 stream flow gauges and 18 ag-met stations, and controls 50 automated gates. Fig. 5 displays the MRGCD telemetry network.

Control Software

Measurement, automation, and telemetry components were developed simultaneously, but largely independent of one another. Although each component functioned as expected, components did not exist as a harmonious whole, or what could truly be called a SCADA system. The missing component was software to tie all the processes together. There are a variety of commercially available software packages for such use and MRGCD experimented with several. Ultimately, the MRGCD chose to purchase the commercial software package Vsystem (Vista Controls, Los Alamos, NM) and to employ the vendor Vista Controls to develop new

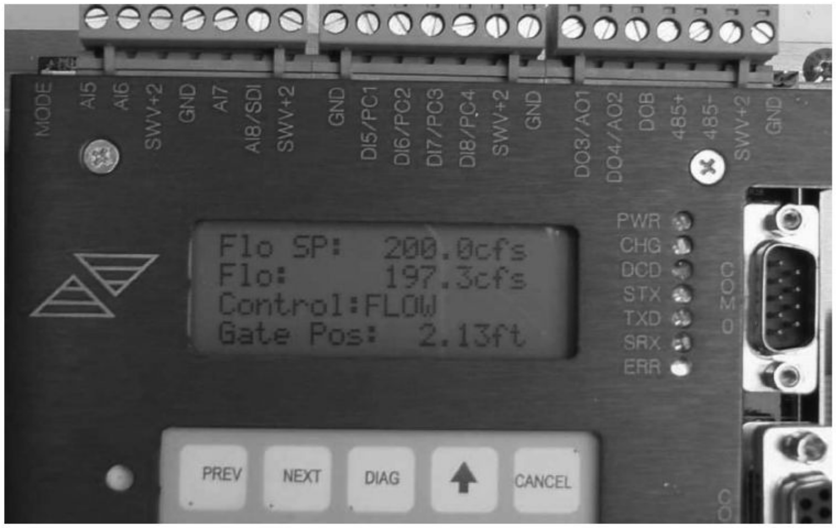

Fig. 4. CDI controller

features specific to the control of a canal network. Installation and setup was done by the MRGCD. This system, known affectionately as the SHAHS (supervisory hydro-data acquisition and handling system), gathers data from RTUs on a regular basis. With the capability to define both timed and event driven poll routines, and specify a virtually unlimited number of RTUs and MODBUS PLC (SCADA communication protocol; programmable logic controllers) registers to collect, virtually any piece of information can be collected at any desired time. The Vsystem software can process data through a myriad of mathematical functions, and combine outputs from multiple stations. Vsystem also incorporates the ability to permanently store data in its own internal database, MS Sequel databases, or export data in other formats. Data can be displayed in a user-created graphical user interface (GUI) which MRGCD water operations personnel use to monitor water movement. The screens can also execute scripts to generate data, control parameters, control gate set points, and monitor alarm conditions for automated control structures. Finally, the GUIs can be used to control automated structures by transmitting new parameters and setpoints. Fig. 6 shows a Vsystem screen displaying check structures and pools on a main canal, and Fig. 7 illustrates a Vsystem control screen for a Langemann gate.

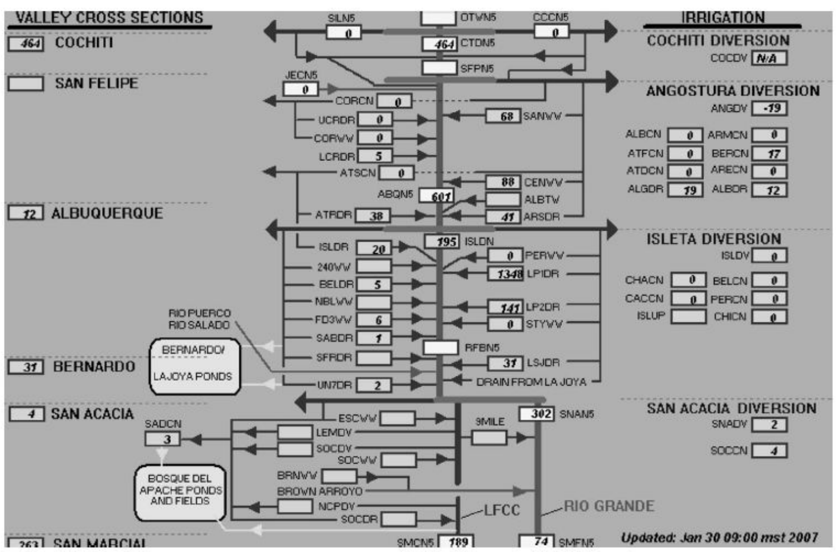

Fig. 5. MRGCD telemetry network

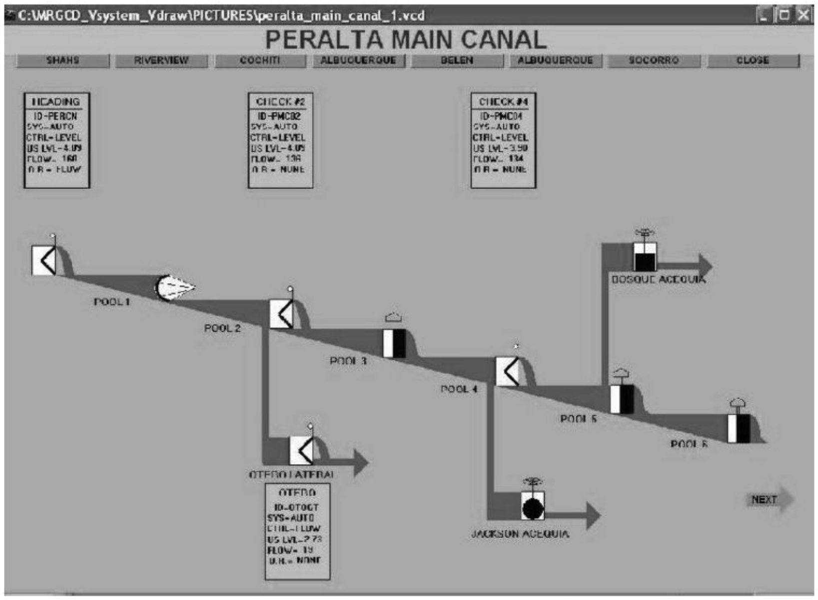

Fig. 6. Vsystem screen displaying check structures and pools on a main canal

Decision Support System for Scheduled Water Delivery

A new and very useful component is currently being incorporated into the MRGCD SCADA system. A decision support system (DSS) had been developed by Colorado State University to encompass irrigated agriculture in the MRG (Oad et al. 2009; 2006). A forthcoming article describing the DSS will be published soon (Oad et al. 2009). The DSS simulates soil moisture and includes a model to calculate crop water demands for lateral service areas on a real time basis (Oad et al. 2009; Oad and Kinzli 2006). The model then develops optimum water delivery schedules to meet crop demands. The DSS will give MRGCD operators a required

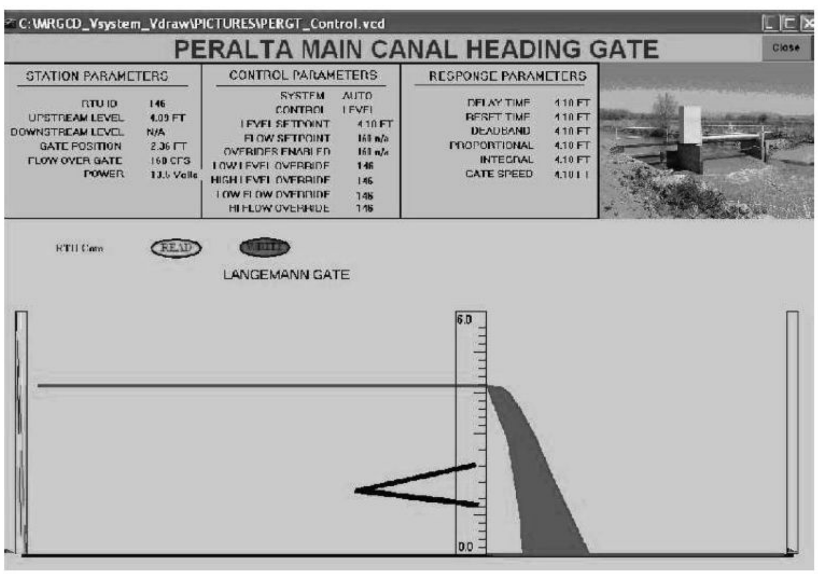

Fig. 7. Vsystem control screen for a Langemann gate

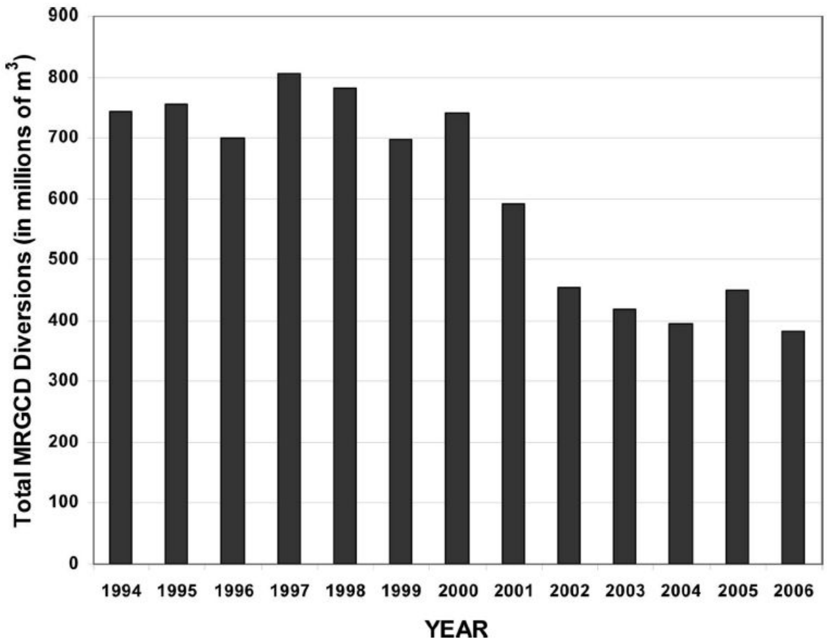

Fig. 8. MRGCD river diversions by year

irrigation delivery on a lateral level based on crop demand. This required delivery will be imported into the GUI of the MRGCD SCADA system so that actual deliveries along the canal system can be compared to DSS recommended deliveries. Incorporating the DSS with the MRGCD SCADA system will involve two steps. First, the DSS output will have to be converted to a format that the Vsystem software can recognize. Vista Systems uses SHEF. A file format for data coming into the SCADA system and the entire MRGCD gauging network is set to function on this format. The data for each individual gate or measuring site is characterized by a distinct data stream in Vsystem and can then be linked to the appropriate node in the SCADA GUI. The data stream to use for each node in the GUI is user specified and therefore nodes can be created that can display DSS recommended flow rates. This GUI will allow water managers to remotely change automated gate settings so that actual diversions closely represent water requirements. This will provide better water management within the MRGCD and allow for a minimized river diversion as the required and actual diversion values converge.

Results and Conclusions

The adoption of new technology has resulted in a simple, inexpensive, and reliable SCADA system. When coupled with modified operational practices, the results have been significant. A decade ago the MRGCD was diverting over 7.4×10^8 m^3/year from the Rio Grande. This large diversion was significantly higher than the required crop demand and resulted in water being returned downstream through drains. Over the last 3 years diversions have averaged less than 4.3170×10^8 m^3/year. Fig. 8 displays the MRGCD river diversions by year. With a district-wide farm delivery requirement of 2.3436×10^8 m^3/year, there is still the opportunity to further minimize river diversions. The incorporation of the previously mentioned DSS will greatly assist the MRGCD in reducing diversions to more closely represent the required crop demand in the coming years.

Although many irrigators miss the old days of unscheduled on-demand water delivery, they have reaped a major benefit from these changes (USGS 2008). New Mexico has experienced a decade of drought and reservoir storage has been minimal. Due to the modernization and accompanying improvement in efficiency, a much smaller volume of water is released from upstream storage reservoirs to meet a given demand. Therefore, the limited supply of stored water is stretched farther. During the 2002 and 2003 irrigation seasons the impact of the severe drought was minimized and the MRGCD only had to curtail deliveries for short periods of time, allowing irrigators to receive their full annual deliveries.

Additionally, New Mexico has done unusually well in meeting Rio Grande Compact delivery obligations over the last few years. This is due to many factors, but one major reason is the more efficient movement of water through the middle valley by the MRGCD. Annual carryover storage has also increased as a result of efficiency improvements. This translates to less empty storage space to fill during spring runoff, which leads to more water going downstream during runoff, mimicking the hydrograph before the advent of storage reservoirs. This is a subtle change, possibly overlooked by many, but one which may ultimately provide more good for endangered species and the general welfare of the river system than additional artificial releases for those purposes.

Acknowledgments

The writers would like to thank Subhas Shah, the MRGCD Board of Directors, the New Mexico Interstate Stream Commission, the New Mexico Office of the State Engineer, the Middle Rio Grande Endangered Species Act Collaborative Program, the United States Army Corp of Engineers, and the United States Bureau of Reclamation for the assistance and the financial support to undertake this project. Also, the exceptional support of Jim Conley at CDI, Gerald Robinson and Lee Allen at Aqua Systems 2000, and Cathy Laughlin and Peter Clout of Vista Control Systems is graciously recognized.

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APPENDIX P: ARTICLE IN MRGCD NEWSLETTER

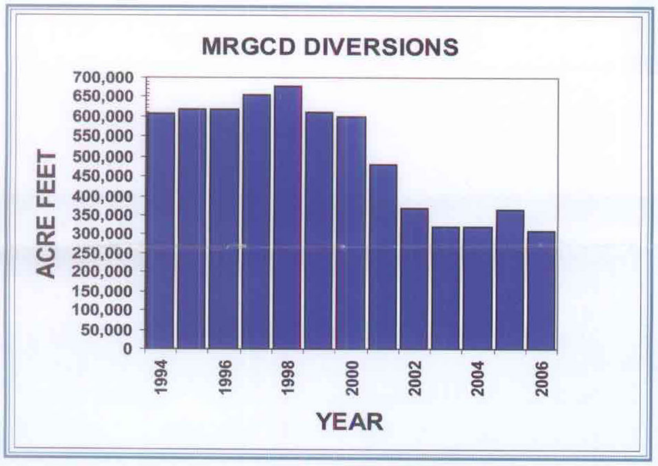
CONSERVANCY TODAY

Keeping the Valley Green

Computer Irrigation Scheduling Software to Remove Guesswork for Irrigators

For the past 10 years the Middle Rio Grande Conservancy District has been using technology and automated gates to more efficiently get water to farmers and their crops. The improvements have helped the District cut by about 45 percent the amount of water it diverts from the Rio Grande each irrigation season.

Now, more improvements are on the way, and the District will be better able to serve farmers and their crops while maximizing the use of water.



Beginning with the 2008 irrigation season, the District will start using a computer modeling program called the Decision Support System (DSS) to help water managers and farmers determine when, how often and for how long they need to irrigate.

The system will gather and sort through all kinds of information—like what types of soils are in an area, how much water that soil can hold, what types of crops are being grown, weather parameters that determine how quickly crops use moisture—process the information, and give the District a more accurate idea of how much water will be needed where at a given time, and for how long the water will be needed. Based on that information and the program's recommendations of when to irrigate and how much water will be needed, the District will be able to more effectively schedule water deliveries.

The DSS for irrigation scheduling is the result of the cooperative work between the New Mexico Interstate Stream Commission, Colorado State University and the MRGCD. The Interstate Stream Commission has sponsored the project for the past five years and has provided most of the funds for it. Sponsorship has also been provided by the Middle Rio Grande Endangered Species Act Collaborative Program.

The program is being developed by a team of researchers from CSU and the ISC led by Dr. Ramchand Oad and Dr. Nabil Shafike. It will first be used in the Belen Division, which has 5,000 irrigators and 25,000 acres of irrigated cropland.

"The system will be able to assist District water managers to more efficiently plan and implement their water delivery operations, thereby reducing river diversions. This will take the guess work out of irrigating and bring a little more logic to the system," Oad says. "We'll know how much water we have and how much farmers will need. It's like trying to run the finances in a household; if you don't know what is coming in and what is going out, you will soon be broke."

Dr. Oad, and the staff of the MRGCD and ISC will hold informational meetings about the DSS in the coming months.

"We really think this will be a tool that will help us better serve our irrigators," says MRGCD hydrologist Dave Gensler. "We're doing all we can to help them."

Oad says the DSS combines the intellectual resources of the user with the capabilities of computers to improve the quality of decision-making.

"It is a logical arrangement of information, including field data related to the type of soils and crops grown by farmers, and is used by water managers to make informed decisions," Oad adds. "In irrigation systems, a DSS can organize information about water demand in the service area and then schedule available water supplies to efficiently fulfill the demand."

APPENDIX Q: NEWSLETTER DISTRIBUTED TO WATER USERS ON THE PERALTA MAIN CANAL

Irrigation Scheduling Update for Peralta East Service Area in the MRGCD Belen Division

Dear Water User,

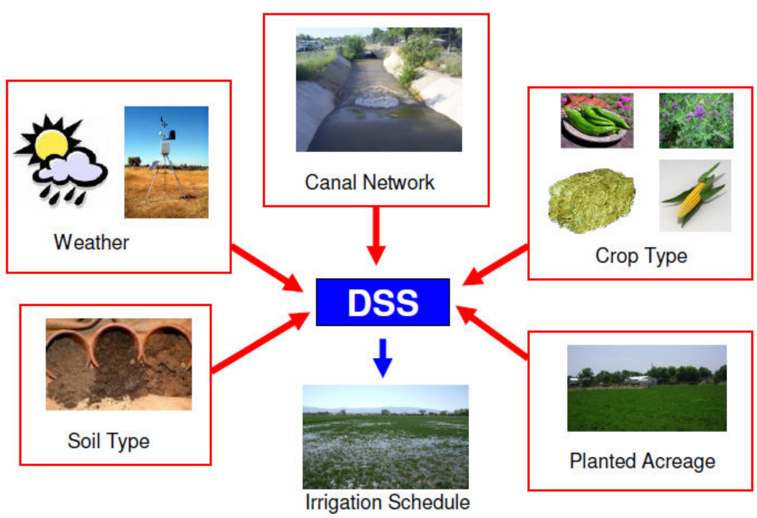
For the past ten years the Middle Rio Grande Conservancy District has used technology and automated gates to more efficiently deliver water throughout the valley. Due to operational issues such as decreased head in ditches and some water users cutting off other scheduled farmers, the MRGCD began implementing irrigation scheduling in March 2009. Scheduling began in the Peralta Main Canal service area in the Belen Division, which is fully modernized and provided with automatic control gates. The Belen Division staff responsible for water deliveries was fully trained in scheduling water deliveries before the start of the season, and is being aided by the computer modeling program called the MRGCD Decision Support System (DSS).

MRGCD Policy and Board Support

Some water users perceive irrigation scheduling and the DSS as completely new initiatives; but in reality, they are not. Water delivery scheduling was practiced before in the district, and the MRGCD policy regulations clearly state that water users need to schedule irrigations with ditch riders. In the October 27, 2008 MRGCD Board meeting David Gensler made a presentation explaining the DSS and scheduled water delivery practice and scheduling plans for the year 2009 irrigation season. The MRGCD Board reemphasized their complete support for the scheduled water delivery practice utilizing the DSS as an advisory tool.

Use of Computer Software for Scheduling Irrigations

The MRGCD DSS calculates how much moisture is initially stored in the soil and then tracks moisture uptake by growing crops. Once crops have used the stored moisture in a service area, the model advises scheduling irrigation to replenish moisture in that service area. With the use of the computer model, the district staff can better forecast how much water will be needed, where that water will be needed, and for how long it will be needed. This



knowledge is being shared with ditch-riders so that they can be better prepared for their irrigation operations. The MRGCD DSS has been developed over the last five years through a collaborative effort between the MRGCD, the New Mexico Interstate Stream Commission, and the Colorado State University. Additional information regarding the DSS is available at www.mrgcd.com under the Decision Support tab on the left side of the screen.

The MRGCD DSS is currently being used to develop irrigation schedules in the form of a calendar which determines when certain lateral canals need to be running to meet crop demand. The calendars are allowing irrigators to plan their water use and provide for a more reliable water delivery method. Without calendars or scheduling, water deliveries were often unreliable and unpredictable. Creating schedules that address water deliveries in advance allows managers to adjust deliveries upstream accordingly. Please know that DSS advices the MRGCD Division staff on how much water to put in main and lateral canals and when to open and close particular laterals. Before a lateral is "on", all water users are expected to schedule their irrigations with their ditch rider so that he can ensure all water users receive full-head water deliveries. DSS does not replace the necessity of scheduling irrigations with ditch rider, especially to avoid the problem of unscheduled water users "cutting off" scheduled water users.

Provisional Schedule For Tome For Year 2009
Total Acres 790
Schedule Subject to Change

May

Sun	Mon	Tues	Wed	Thur	Fri	Sat
					1 35 cfs	2 35 cfs
3 35 cfs	4 35 cfs	5 35 cfs	6 35 cfs	7 35 cfs	8 35 cfs	9 35 cfs
10 35 cfs	11 35 cfs	12 35 cfs	13 20 cfs	14 20 cfs	15 10 cfs	16 10 cfs
17 10 cfs	18 10 cfs	19 10 cfs	20 10 cfs	21	22	23
24	25	26 35 cfs	27 35 cfs	28 35 cfs	29 35 cfs	30 35 cfs
31 35 cfs						

Why Now?

The MRGCD is entering into a situation where there are potentially more water users resulting in increased demand for the same limited amount of water in the Middle Rio Grande Valley. The MRGCD is the largest water user in the region, which is fine, as long as water use is efficient. Before considering scheduling, the district has made efficiency gains through the use of modernized controlled gates, better measurements, and now more efficient operational procedures. The MRGCD is now utilizing the capabilities provided by modern control gates and measurements to better schedule irrigation deliveries, which was not possible before. Historic deliveries were on adhoc basis and this resulted in water users cutting each other off and decreased head in the ditches, which amounted to lost time for the irrigator and wasted water.

Using the analytical power of computers, the district is monitoring weather patterns and climatic variables to forecast crop water requirements. The current scheduling allows the ditches to be run full in a rotational fashion, which increases head and decreases irrigation time. By scheduling water delivery using the MRGCD DSS, the district is providing more disciplined, reliable, and equitable water delivery to all users.

Recognition of Farming as a Complicated Operation

The MRGCD recognizes that even with the certainty that scientific calculations can bring, these calculations cannot account for inherent complexity associated with farming. The district incorporates a significant amount of flexibility into the scheduling to account for this complexity. The ditch-riders are in constant contact with the water users and are determining whether the schedules are working or if they need revisions. There will always be special situations such as vegetable crops and new planting that will require water more frequently and the ditch-riders have been dealing with those situations by making extra water available. The ditch-riders have also been equipped with portable soil moisture sensors and if concerns arise they can determine water needs for individual fields. Additionally, in April 2009, the MRGCD Board meeting was held in Belen to address farmers concerns regarding scheduled water delivery and water delivery operations. The farmers concerns were well received and will be incorporated into the new set of irrigation schedules.

The MRGCD DSS is currently being used for the Peralta Main Canal and all of the laterals that are fed by the Peralta Main Canal in the Belen Division. Overall, scheduling since March has been successful in several aspects. The schedules have resulted in increased head in the irrigation ditches, increased reliability in water delivery, and efficiency improvements. From a management standpoint, the MRGCD DSS has resulted in a much more organized protocol for delivering water by determining water delivery targets in advance, which allows managers to adjust deliveries upstream accordingly. Over time, scheduled water delivery and the MRGCD DSS will be used throughout the entire district. For any questions, comments, please feel free to contact any of the following.

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Dr. Ramchand Oad, Colorado State University, Ramchand.oad@colostate.edu
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